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The external costs of pasture weed spread: an economic assessment of serrated tussock control

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Abstract

The external cost associated with the spread of pasture weeds such as serrated tussock (*Nassella trichotoma*) is an important economic problem. This problem is complicated in many parts of south-eastern Australia where low rainfall and low soil fertility prevent the economic viability of control of this weed through pasture improvement. A consequence of serrated tussock spread in this region has been calls for increased public intervention in its control. However, because there have been no attempts to measure the external costs of serrated tussock spread, one of the major economic grounds on which this activity might be justified has not been quantified. The purpose of this paper is to provide this information. A stochastic simulation model is developed to determine the size of the external cost associated with the spread of serrated tussock and to evaluate the economic benefits of a range of control scenarios. It is concluded that on low rainfall-low soil fertility country the socially optimal control option for serrated tussock is to retire land from agriculture and re-vegetate it with trees. ©2000 Elsevier Science B.V. All rights reserved.

Keywords: External costs; Weed spread; Stochastic simulation; Australia

1. Introduction

One of the least studied areas of weed research has been to evaluate the external costs of weed spread. External costs result when the actions of individuals impose uncompensated costs on others. Spreading weeds impose external costs where they adversely affect the economic welfare of other landholders, both private and public. These costs indicate a divergence between the private and socially desirable optimal level of weed control. They are thus a component of the overall social costs attributable to weeds and vary according to the rate of spread, the nature of the production systems affected and the prevailing environment. Where the rate of spread is rapid, the greater is the private–social divergence in control requirements and the stronger is the rationale for public intervention in facilitating weed control (Auld et al., 1987).

External costs are important in relation to weed spread because they are a primary indication of the concept of market failure that is a central issue in proposals for policies of public intervention in weed control. Pannell (1994) considered that market failure pervaded most of the weed management activities of governments. Of the 11 types of market failure that were categorised as being relevant to all weeds, nine were characterised by external costs. The first two categories concerning the spread of weeds between farms

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and from farms to the environment are particularly relevant to pasture weeds. Pannell considered that the appropriate public response to these external cost problems was through direct control and legislation where farms were the source of weed spread in the expectation that such activity would generate greater social benefits than the operations of the free market.

Serrated tussock (*Nassella trichotoma*) is a major weed of pastures in south-eastern Australia given that it has no grazing value because of its high fibre and low protein content and has a propensity to invade and colonise desirable pastures. The main components of the economic problem caused by serrated tussock are the reduced livestock production caused by infestations in pastures, the costs of control with herbicides and improved pastures and the external costs of spread. While the first two components have been well researched (Vere et al., 1980; Edwards and Freebairn, 1982; Vere et al., 1993; Jones and Vere, 1998), the third has not. The external cost aspect of the serrated tussock problem is now assuming greater prominence as the weed becomes more concentrated in the more marginal agricultural areas. While there has been a long history of successful serrated tussock control by landholders and local government, it is apparent that such direct control methods have been ineffective under unfavourable environmental and economic conditions (Vere et al., 1993). The problem of serrated tussock in these areas persists because many landholders cannot undertake profitable control and this results in the infestation of other areas.

Serrated tussock is now well established in large areas of south-eastern Australia in which the soil fertility and rainfall environments prevent economic control under the preferred method of replacement by improved pastures. Heavy infestations of the weed in such areas are a source of infestation to both neighbouring and distant lands as serrated tussock seeds can disperse over long distances. Recent surveys in 1994 (Gorham, unpublished) and in 1997 (Jones and Vere, 1998) found that the total area of serrated tussock in New South Wales was 9 and 30% higher than an earlier estimate by Campbell (1987). Of a total area of approximately 887,000 ha infested by serrated tussock (Jones and Vere, 1998), 14.1, 24.7 and 61.2% was classified as being heavily, moderately and lightly infested, respectively. The Monaro region had 18.1% of the total area of serrated tussock and importantly, 28% of the heavy infestations which was double the state proportion of heavy to total infestation. In 10 years, heavy serrated tussock areas in the Monaro increased from 2400 to 35000 ha. This temporal change evidence indicates that serrated tussock is a prominent example of the external cost problems caused by weed spread.

The external cost aspects of the spread of serrated tussock are now attracting considerable public concern. Recognition that the problem of this weed in low potential agricultural country has moved beyond the private control decision context has given rise to proposals for increased levels of public intervention (Anon., 1998). As Pannell (1994) has indicated, the presence of market failure and net social benefits comprises the economic rationale for such activity. As the existence of external costs is a foremost condition in the demonstration of market failure, there is a need to evaluate these costs in a logical and consistent manner.

The purpose of this paper is to evaluate options for reducing the external costs associated with the spread of serrated tussock. A stochastic simulation model is developed which incorporates two options for controlling serrated tussock by landholders and one option for public control. While the paper does not attempt to develop a case for public intervention in serrated tussock control, such policies are closely linked with any analysis of the external cost problem.

2. Modelling weed spread

Auld and Coote (1980, 1981) described the rate of weed spread in terms of; (i) population growth rate at a primary infection site, (ii) the proportion of annual population increase which is dispersed beyond the boundaries of the infection site; (iii) the area over which the fraction (ii) is dispersed, and (iv) the susceptibility of invaded areas to colonisation. It has been suggested that invading weed species have a constant exponential rate of population growth (Harper, 1977). Auld and Coote (1980, 1981) used an exponential population growth model for a weed-affected farm represented by Eq. (1).

$$P_n = \frac{P_0}{100}\left[1 + \frac{c}{100}\right]^n, \quad n = 1, \ldots, T \tag{1}$$

where P_n is the population in terms of the percentage of area infested in year n (taking values between

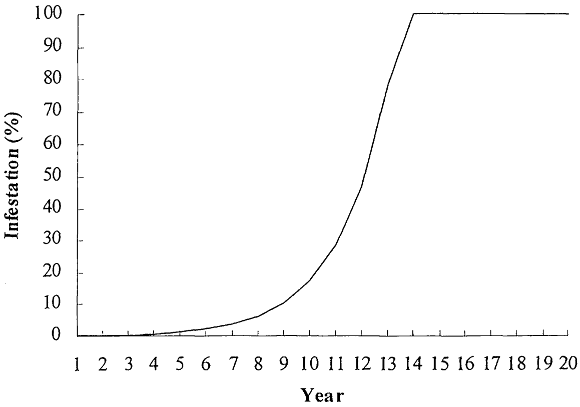

Fig. 1. Exponential weed spread.

0 and 100), P_0 is the initial population, c is a constant rate factor, and T is the time to full infestation. In this model, population growth continues until $P_n = 100$, when complete infestation occurs and P_n remains constant. For the spread of serrated tussock, values of 15–20 years to reach full infestation have been observed in naturalised pasture systems. To illustrate the exponential growth model a hypothetical weed spread function is presented in Fig. 1 using parameter values of $P_0 = 2$ and $T = 15$. To derive the function in Fig. 1 the first step is to determine the constant, $(1 + c/100)$, by substituting the appropriate values for P_n and T into Eq. (1).

$$P_{15} = \left(1 + \frac{c}{100}\right)^{15} = 100$$

$$15\left[\log_{10}\left(1 + \frac{c}{100}\right)\right] = \log_{10}(100)$$

$$\log_{10}\left(1 + \frac{c}{100}\right) = 0.1333$$

$$1 + \frac{c}{100} = 1.359$$

The annual levels of weed infestation illustrated in Fig. 1 were thus estimated from the following equation:

$$P_n = \frac{P_0}{100}\,[1.359]^n \quad \text{with} \quad P_0 = 2$$

For a weed such as serrated tussock, where wind is the main seed dispersal agent, a small proportion of seeds are distributed significant distances from the parent plant. Approximately half of the seeds fall near the parent prior to the inflorescences being dispersed by wind, the remainder are transported in the inflorescence to spread on and beyond the farm. In relation to the annual increment in population growth, it is reasonable to assume that the dispersal fraction from one farm to others is a constant from year to year. If a fixed proportion, s, of the annual population increase occurs beyond the farm then Auld and Coote (1980, 1981) propose annual population growth (on the farm) as;

$$P_n = \frac{P_0}{100}\left[\left(1 + \frac{c}{100}\right)\left(1 - \frac{s}{100}\right)\right]^n, \quad n = 1, \ldots, T \tag{2}$$

In this study the annual population growth equation as proposed by Auld and Coote (1980, 1981) is reformulated to Eq. (3). This equation has two developments. First, notation (i) is introduced to represent the specific farm infested and, second, it is now a Markov equation as infestation in year n is a function of infestation in year $n-1$ and not the initial infestation in year 0. This latter feature facilitates the modelling of a dynamic system.

$$P_{i,n} = \frac{P_{i,n-1}}{100}\left[\left(1 + \frac{c_i}{100}\right)\left(1 - \frac{s_i}{100}\right)\right], \quad n = 1, \ldots, T \tag{3}$$

Eq. (3) implies that the weed population growth on farm i is reduced to the extent that some of the population growth is dispersed beyond the farm boundary. The first term within the brackets of Eq. (3), $(1 + c_i/100)$, represents the proportional increase in weed infestation while the second term, $(1 - s_i/100)$, represents the proportion of the new infestation dispersed beyond the farm. Consequently, $P_{i,n}$ represents the level of infestation only on farm i in year n, not the total level of infestation derived from the previous farm infestation, $P_{i,n-1}$.

Now consider a neighbour, farm j. Weed population growth on this farm will be a function of increasing density from previous infestations on farm j, plus additional infestations from the dispersal fraction on farm i. This is represented as follows;

$$P_{j,n} = \frac{P_{j,n-1}}{100}\left[\left(1 + \frac{c_j}{100}\right)\left(1 - \frac{s_j}{100}\right)\right] + \frac{P_{i,n-1}}{100}\left[\frac{s_i}{100}\right], \quad n = 1, \ldots, T \tag{4}$$

This process of weed spread may continue with farm j (and possibly farm i) dispersing a fraction of infestation to farm k and so on. Additionally, there is the potential for infestation dispersal from farm j to farm i. If farm j has no initial weed presence, i.e. $P_{j,0}=0$, then the only source of weed infestation is from colonisation by weed dispersal from farm i. However, once this takes place then $P_{j,n}>0$ and population growth can occur from infestations within the farm.

As the parameter s is a proportional increase in infestation from farm i to farm j, it is independent of the size of farm j. Consequently, the area of infestation occurring on farm j in any given year from farm i is calculated as a function of the infested area on farm i by the dispersal fraction. Auld and Coote (1980, 1981) restricted the parameter s to occur only following population saturation at the farm level. Given the nature of seed spread from serrated tussock there appears little evidence to impose such a constraint and the approach adopted here was to allow spread at all population levels.

3. The serrated tussock model

A stochastic simulation model was developed to evaluate management options for reducing the external cost of serrated tussock. Rainfall is the major stochastic variable as it affects pasture productivity, and therefore potential livestock stocking rate, and the establishment success of perennial pastures and trees. The principles of weed spread are explicitly incorporated in the model as is the impact of serrated tussock on pasture and livestock performance.

The model used a Latin hypercube sampling procedure and was solved for 5000 iterations over 25 years at a discount rate of 5%. The solution included estimated means, standard deviations and percentile values for net present value (NPV) for each specific area. The model estimated the benefits of a range of control scenarios and ranked the results according to stochastic dominance (Anderson et al., 1977).

3.1. Land types

The effect of serrated tussock spread on- and off-farm was estimated from Eqs. (3) and (4). The private cost from weed spread was determined by applying Eq. (3) to estimate weed density, while Eq. (4) was used to determine the associated external costs.

The external costs of serrated tussock and the benefits of its control were estimated for two representative land types in a low rainfall environment. Area A comprised of a naturalised pasture on non-arable land with low soil fertility and a heavy serrated tussock infestation. Area B comprised of a fertilised mix of naturalised pasture in arable high fertility country and with no initial serrated tussock. The distribution of spread of serrated tussock over area B, through the dispersal proportion s, was assumed to be uniform. The alternative land types are illustrated in Fig. 2 and are represented by the two concentric rings, the inner circle being area A while the outer ring is area B. The external boundary of area B represents the outer limit to which new infestations can occur. Areas A and B can be thought of as representing farms i and j, but here area B represents an aggregation of three to four farms affected by seed dispersal from farm i (i.e. area A). By treating area B as one large farm, infestation of neighbouring farms in area B is endogenously incorporated through the first term of Eq. (4).

Although serrated tussock seeds have been observed to travel up to 20 km, the large proportion of seeds which lead to new infestations occur on neighbouring farms and consequently travel much smaller distances. Accordingly, the dispersal proportion was confined to a radius of 5 km from the source. It is assumed that weeds are distributed uniformly in area A and the source of the infestation is taken to be the midpoint of the radius of area A, r_A.

Given the relationship between the dispersal proportion (s) and the distance seeds can travel (d) there is a direct relationship between the size of area A and the circumference of area B and accordingly its area. Setting area A to be 1000 ha, the radius (r_A) is calculated at 1.784 km ($r=0.1\sqrt{A/\pi}$)[1]. If $d=5$ the radius of area B (r_B) is 5.892 km [i.e. $5+0.5(1.784)$] and the size of area B is calculated as;

$$B=\pi 100 r_B^2 - A$$

[1] The value 0.1 is simply a constant for converting from hectares to kilometres. Likewise the value 100 in the following equation for calculating the size of area B is a constant for converting kilometres to hectares.

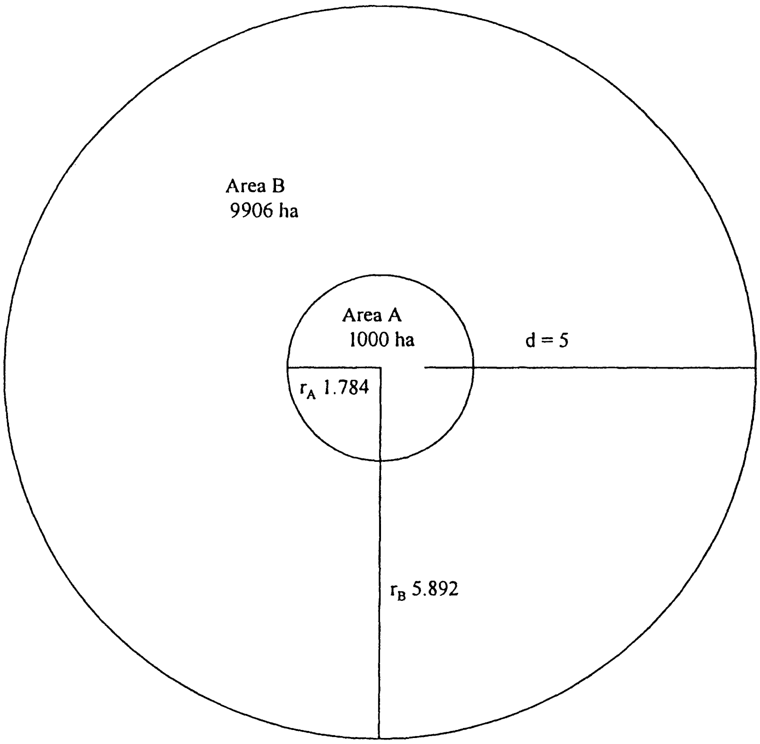

Fig. 2. Land types for measuring weed spread.

where *B* and *A* are the sizes of the respective areas. From this process area *B* was determined to be 9906 ha.

3.2. Control scenarios and annual decisions

Three separate serrated tussock control scenarios were proposed for area *A*. Control options in area *B* were not included as the objective was to evaluate the external cost of weed spread imposed on this region. A 'no control' scenario was used to estimate the impact of each of the control scenarios upon the external cost due to weed spread. A 'no control' scenario is not a serious management option as serrated tussock is a declared noxious weed and by legislation must be controlled. The three control scenarios are described as follows.

Scenario 1: Naturalised pasture with periodic herbicide control. This scenario involves the spraying of a herbicide on a naturalised pasture supporting sheep when serrated tussock exceeds 50% of the area. This is the least cost scenario and given that no additional controls are imposed (such as competitive pasture species) it can be expected that serrated tussock will need to be controlled again within 7–10 years. The main species in this pasture are winter growing *Danthonia* spp., *Trifolium subterraneum*, annual grasses (*Vulpia* spp., *Hordeum leporinum*), and summer-growing *Bothriochloa macra*, *Microlaena stipoides*, *Themeda triandra* and *Stipa* spp. Given the nature of summer and winter production from these pastures, annual rainfall distribution is considered an important determinant of pasture production. As the herbicides used to control serrated tussock can have a negative effect upon some of these species, no livestock can be supported in the year of control. After a herbicide treatment it can take up to 3 years until a pasture fully recovers and, consequently, stocking rates of 50 and 80% of full carrying capacity in the years 2 and 3 after control are assumed.

Scenario 2: Introduced perennial pasture. A successful method of serrated tussock control is to sow a competitive introduced perennial pasture, such as *Trifolium subterranean* with *Phalaris aquatica* and/or *Dactylis glomerata*, after spraying. If successfully established, these species can replace serrated tussock on infested areas and provide long-term control. On non-arable low fertility country, the probability of successful establishment is low due to the difficulty in establishing pastures by aerial seeding in dry years. The two critical periods for rainfall which determine whether establishment will be successful are June to August and September to December. If rainfall is deficient in either of these two periods, a perennial pasture will fail to establish and re-sowing will be necessary when seasonal conditions permit. Rainfall from May to December determines production once the pasture is established from the air. The treated area should be rested from grazing for 1 year following sowing to ensure maximum weed control from sown pastures. As it takes 3–4 years for a newly established perennial pasture to reach full production, pasture production in years 2 and 3 following the establishment were set to be 50 and 80% of full production, respectively.

Scenario 3: Tree establishment. Vere et al. (1993) demonstrated that it is unprofitable to control serrated tussock by pasture improvement in non-arable areas with low rainfall and low soil fertility. Campbell and Nicol (1996) proposed that the establishment of trees to control weeds would be a more sustainable option in such situations. Tree varieties that achieve this goal are *Pinus radiata* and various species of *Eucalyptus*. The objective of tree planting is solely for weed control and no financial returns, either from agroforestry or firewood, are to be expected. This means that the land is withdrawn from agricultural production. Rainfall between May and December determines the success or failure of tree establishment. If drought conditions prevail during this period then tree establishment has failed and would need to be repeated the following year. Once trees have established, moderate variations in climate do not have a significant effect upon the efficacy of serrated tussock control by trees.

The capital and annual variable costs for the scenarios are given in Table 1. The details of the annual management decisions for the three control scenarios are given in Table 2.

Table 1
Capital and variable costs associated with control strategies

	Capital cost ($/ha)	Variable cost ($/ha)
Naturalised pasture — herbicide control	100	–
Maintain naturalised pasture	–	15
Establish perennial pasture	286	–
Maintain perennial pasture	–	90
Establish trees	725	–

Table 2
Annual decisions associated with control strategies

Decision	Description	Scenario
1	Control naturalised pasture with herbicide	1
2	Graze naturalised pasture — year 2	1
3	Graze naturalised pasture — year 3	1
4	Graze naturalised pasture — year 4 and onwards	1
5	Establish an introduced perennial pasture (phalaris)	2
6	Graze perennial pasture — year 2	2
7	Graze perennial pasture — year 3	2
8	Graze perennial pasture — year 4 and onwards	2
9	Establish trees	3
10	Grow trees	3

3.3. Control effects

The dispersal proportion s_A (i.e. dispersal from area A) was set at 5 which, due to a lack of more objective information, was obtained from anecdotal evidence. For Scenario 3 it was assumed that trees reduced seed dispersal by 95% from a combination of the tree cover and increased competition from other plant species that establish once serrated tussock and livestock are removed from the system. The number of years until full infestation, T, was set at 15, 30 and 100 for scenarios 1, 2 and 3, respectively. The effect of the different control methods was to reduce the level of infestation in the year of treatment. The new level of infestation following control was 3% (i.e. $P_{A,n}=3$, a 97% weed kill) for each control decision. The initial weed infestations were set in the model at $P_{A,0}=80$ and $P_{B,0}=0$.

3.4. Climatic effects

Rainfall is a critical determinant of pasture production, and therefore carrying capacity, and the efficacy of the control decisions. Four climatic scenarios were developed to represent the normal range of rainfall

Table 3
Rainfall probability distributions

Rainfall period	Distribution type	Mean	Standard deviation
Annual	Lognormal	480.86	142.33
June to August	Lognormal	83.42	48.44
September to November	Lognormal	125.90	67.75
May to December	Normal	289.26	90.85

conditions in the region — drought, dry, median and favourable. Monthly rainfall data for the township of Dalgety between 1896 and 1994 was used to construct each climatic scenario and determine the associated probabilities of occurrence.

Four rainfall periods were derived; annual, June to August, September to November, and May to December. Annual rainfall was used to estimate production of native pastures. The two rainfall periods June to August and September to November were used to estimate the success or failure of establishing a perennial pasture. The period May to December was used to estimate the production of an established perennial pasture and the success or failure of tree establishment.

The appropriate probability distribution for rainfall is expected to be either a normal distribution or a lognormal distribution to account for any possible skewness in the data. For the four rainfall periods various probability distributions were tested for goodness of fit and the distributions and parameters chosen are given in Table 3.

3.5. Pasture production

The production of naturalised and perennial pastures was based on the daily pasture growth curves for poor, average and good growing conditions, represented by the 25th, 50th and 75th percentiles (McDonald, 1995). These descriptions corresponded with the dry, median and favourable descriptions used in this analysis and McDonald's seasonal trends were used for both naturalised and perennial pastures, with a drought category included and calculated at the 10th percentile of pasture dry matter production (Table 4). An 'expert' panel approach was used to estimate the production differences in the monthly growth curves for different soil fertility and rainfall conditions.

The livestock enterprise considered was a Merino wether system producing 21 μm wool. The potential livestock carrying capacity [2] for each soil fertility, pasture type and climatic scenario were determined from a linear programming model of southern New South Wales (Table 5) which incorporated the seasonality of pasture supply and livestock feed demands (Jones and Vere, 1998).

Table 4
Climatic effects on pasture production by seasonal growing condition (kg DM/ha)

	Growing conditions			
	Drought	Dry	Median	Favourable
High fertility				
Perennial pasture	2421	4841	9630	16416
Good native pasture	1159	2318	4725	9486
Poor native pasture	587	1174	2490	4847
Medium fertility				
Perennial pasture	1936	3873	7701	13133
Good native pasture	927	1854	3780	7589
Poor native pasture	470	939	1992	3878
Low fertility				
Perennial pasture	1452	2905	5778	9850
Good native pasture	695	1391	2835	5691
Poor native pasture	352	704	1494	2908

Table 5
Climatic effects on stocking rate by seasonal growing condition (DSE/ha)

	Growing conditions			
	Drought	Dry	Median	Favourable
High fertility				
Perennial pasture	0.5888	1.1761	4.7201	16.0406
Good native pasture	0.5058	1.0117	3.9781	6.1422
Poor native pasture	0.0854	0.1708	0.5754	0.9399
Medium fertility				
Perennial pasture	0.4710	0.9409	3.7761	12.8325
Good native pasture	0.4046	0.8094	3.1825	4.9138
Poor native pasture	0.0683	0.1366	0.4603	0.7519
Low fertility				
Perennial pasture	0.3533	0.7057	2.8321	9.6244
Good native pasture	0.3035	0.6070	2.3869	3.6853
Poor native pasture	0.0410	0.1025	0.3452	0.5639

[2] Stocking rates are reported on the basis of dry sheep equivalents (DSE) per hectare. A DSE is a rating based on the amount of energy required to maintain a 50 kg wether per annum.

3.6. Weed effects

Following the approach of Denne (1988) and Jones and Vere (1998) it was assumed that there is a linear relationship between weed density and pasture yield loss. Thus, if a serrated tussock infestation is 40% of an area, there is expected to be a 40% reduction in pasture production.

Cousens (1985) has argued that the appropriate yield loss function for annual crops is a rectangular hyperbola because at low densities weeds are most competitive to crops and hence cause a maximum marginal reduction in yield. The effect of an increase in weed numbers at low densities is additive. However, when the density is high increased intra-specific weed competition tends to reduce the marginal yield loss. The function that Cousens derived was;

$$Y_{\mathrm{L}} = \frac{ID}{1 + (ID/A)} \tag{5}$$

where Y_{L} is percentage yield lost because of weed competition, D is weed density (plants per square metre), I is the percentage yield loss per unit weed density as weed density approaches zero, and A is an estimate of the maximum yield loss of a weedy crop relative to the yield of a weed free crop.

This hyperbolic yield-loss function has been validated (Cousens et al., 1984; Martin et al., 1987) for annual crops where weeds are measured in terms of some land unit, such as plants per square metre. There have been few attempts in pasture systems to either validate the hyperbolic function or estimate the most appropriate functional form for yield loss when weed infestations are reported on a percentage infestation. As a result, in the absence of any better information the simpler linear yield loss relationship has been adopted here.

3.7. Economic effects

The economic performance measure used in this analysis is the NPV of annual profit over a 25 year simulation period. NPVs were calculated separately for area A, area B and the combined total of the two areas. The annual profit function for both area A and area B was calculated as follows;

$$\pi_{i,n} = H_i \left[\left(1 - \frac{P_{i,n}}{100}\right) \mathrm{SR}_{s,k,n}\, \mathrm{GM} - \mathrm{AC}_n - K_n \right] \tag{6}$$

where $\pi_{i,n}$ is the profit of the ith region in year n, H is the area (hectares) of the ith region, $P_{i,n}$ is the level of infestation on the ith area in year n, $\mathrm{SR}_{s,k,n}$ is the stocking rate of the kth pasture type in the sth season in year n (Table 5), GM is the annual sheep enterprise gross margin ($15.40 per DSE), AC are annual operating costs and K are capital costs (Table 1). The parameter i can take values of A for area A, B for area B and T for the total area where $\pi_{T,n} = \pi_{A,n} + \pi_{B,n}$. For scenario 3, SR was set to zero so $\pi_{A,0} = -725{,}000$ (i.e. –$725 × 1000 ha) and zero thereafter. The discount rate used was 5%.

4. Results

4.1. Level of serrated tussock infestation

The expected level of serrated tussock infestation of both area A and area B for each control scenario (Fig. 3) was derived from a deterministic version of the model. Application of control scenario 3 resulted in infestation levels close to zero in both areas and was not plotted. Implementation of scenarios 1 and 2 both reduced the level of infestation on area A, however, within a 7–10-year period significant re-infestation had occurred and control was again necessary. Reliance upon either scenario 1 or 2 to control serrated tussock infestations in area A resulted in a significant level of infestation in the previously unaffected area B within 20 years.

4.2. Benefits of the control options

The 'no control' scenario for area A was run in addition to the three control scenarios to compare the economic benefits of each scenario for area A, area B and the total area. Reported in Table 6 are the minimum, maximum, mean and standard deviation of NPV for each scenario.

Area A: The 'no control' scenario resulted in a mean NPV for area A of −$211,409. Scenario 2 was the only control option that gave a positive mean NPV for area A ($314,642). Relying upon scenario 1 caused economic losses (−$358,047) from the combination

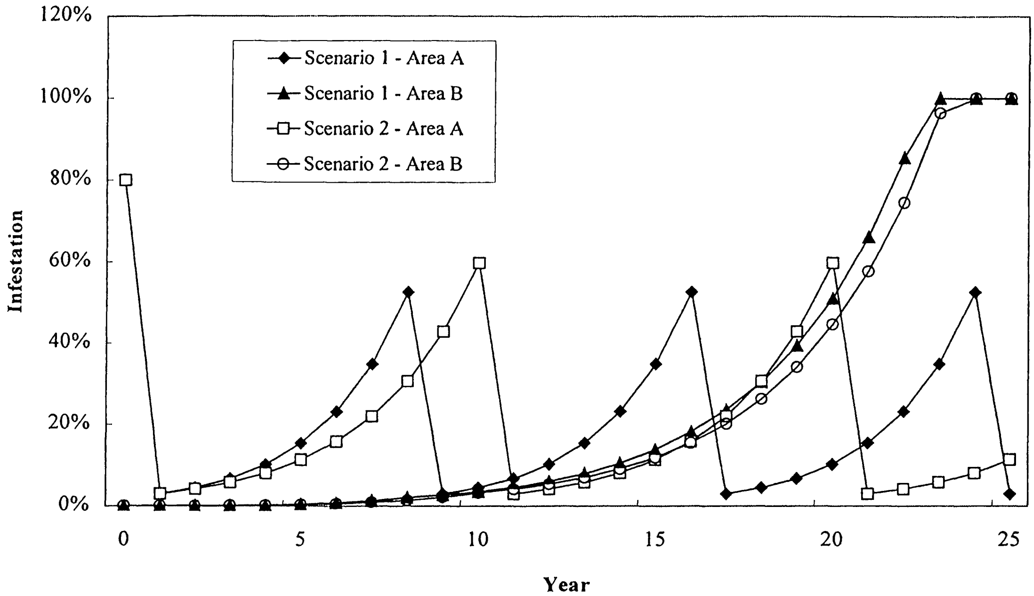

Fig. 3. Infestation of serrated tussock on areas *A* and *B* for scenarios 1 and 2.

Table 6
Simulation model NPV results ($)

	Minimum	Maximum	Mean	Standard deviation
No control				
Area *A*	−211409	−211409	−211409	0
Area *B*	164901	2454092	1377136	334035
Total	−46508	2242683	1165727	334035
Scenario 1				
Area *A*	−368935	−347031	−358047	3298
Area *B*	4439285	7562788	6051184	482760
Total	4070786	7215757	5693137	485597
Scenario 2				
Area *A*	−186775	776226	314642	154602
Area *B*	4675246	8305960	6323640	519017
Total	5016550	8276932	6638282	505698
Scenario 3				
Area *A*	−1348073	−690476	−693326	43194
Area *B*	5648109	9450052	7724302	523733
Total	4957632	8759576	7030976	524939

of high control costs and low stocking rates. Tree establishment has high capital costs and no annual income, consequently the mean NPV of scenario 3 (−$693,326) was the lowest of all the scenarios.

Area B: The 'no control' scenario resulted in the lowest mean NPV ($1,377,136). Scenario 3 resulted in the highest mean NPV ($7,724,302) followed by scenario 2 ($6,323,640) and scenario 1 ($6,051,184). To calculate the external cost associated with the spread of serrated tussock, a 'no weed spread' scenario was run (mean NPV $7,741,601) with the external cost for each scenario being the difference in the mean NPVs. This resulted in calculated external costs of $1,690,417, $1,417,961 and $17,299 in terms of mean

NPV for scenarios 1, 2 and 3, respectively. On the basis of these results, adoption of scenario 3 to control serrated tussock in area *A* would be preferred by landholders in area *B* as it resulted in the minimum external cost being imposed upon them.

The total area: An economic trade-off is involved in protecting production in area *B* by establishing trees in area *A*. The opportunity cost to area *A* ($1,007,968 mean NPV) is represented by the difference in mean NPV between scenarios 2 and 3. Therefore, the combined result from areas *A* and *B* are required to determine the socially preferable scenario. Scenario 3 resulted in the greatest mean NPV for the total area ($7,030,976), which was significantly greater than scenario 1 ($5,693,137 mean NPV) and scenario 2 ($6,638,282 mean NPV).

4.3. Risk aversion and stochastic dominance

Ranking the results on the basis of mean NPV implies risk neutrality by an individual decision maker. There is evidence that most Australian farmers are risk averse (Bardsley and Harris, 1987) and consequently if risk attitudes are taken into account the rankings of the scenarios may change. For example, for the total area the standard deviation of NPV for scenario 3 was greater than the standard deviation of scenarios 1 and 2, implying a greater degree of income variability and risk.

Testing strategies for stochastic dominance is a means of ranking alternative strategies when risk preferences are unknown (Anderson et al., 1977). Stochastic efficiency rules are applied by undertaking pairwise comparisons of the cumulative distribution functions (CDFs) of the scenarios (Fig. 4). On the basis of this analysis scenario 3 was preferred. As scenario 3 exhibited first-degree stochastic dominance no further testing, such as for stochastic dominance with respect to a function (Meyer, 1977a, b) was required.

4.4. Sensitivity analyses

Sensitivity analyses were applied to a number of parameters that were considered variable. These were a higher level of soil fertility for area *A*, different sizes of infestation, a greater dispersal distance, the population dispersal proportion and a lower initial infestation on area *A*. Reported in Table 7 are the results from the sensitivity analysis in terms of mean and standard deviation of NPV for the total area.

Table 7
Sensitivity analysis on soil fertility, size of area *A*, dispersal distance and initial infestation ($ NPV)

	Mean	Standard deviation
Medium fertility		
No control	1623510	283455
Scenario 1	4246150	348457
Scenario 2	4783324	395678
Scenario 3	4656215	355860
Area A of 500 ha		
No control	1991501	290245
Scenario 1	4360789	347024
Scenario 2	4594381	364026
Scenario 3	4618485	353106
Dispersal distance 10 km		
No control	9168800	1179900
Scenario 1	17476060	1335309
Scenario 2	17942930	1369164
Scenario 3	17992120	1345908
Dispersal proportion 10%		
No control	787503	311811
Scenario 1	5765205	471238
Scenario 2	6716380	492717
Scenario 3	7035977	511164
Initial infestation 20%		
No control	2585173	335323
Scenario 1	3763278	367922
Scenario 2	4652386	415935
Scenario 3	4658397	391635

Effect of alternative soil fertility: The analysis was repeated for the case where the soil fertility of area *A* was medium instead of low. Higher soil fertilities have greater potential pasture production and stocking rates and thus, greater opportunity costs from their removal from agriculture. Consequently, the optimal solution for controlling weed spread may differ under alternative soil fertility conditions. Adopting a higher soil fertility for area *A* resulted in scenario 2 being the preferred control option as it had the (marginally) highest mean NPV.

Alternative size in infested area: The size of many motherload areas in the Monaro region may be smaller than the assumed 1000 ha. Reducing the size of area *A* to 500 ha tested the effect of the size of the infested area upon the robustness of the results. There was no

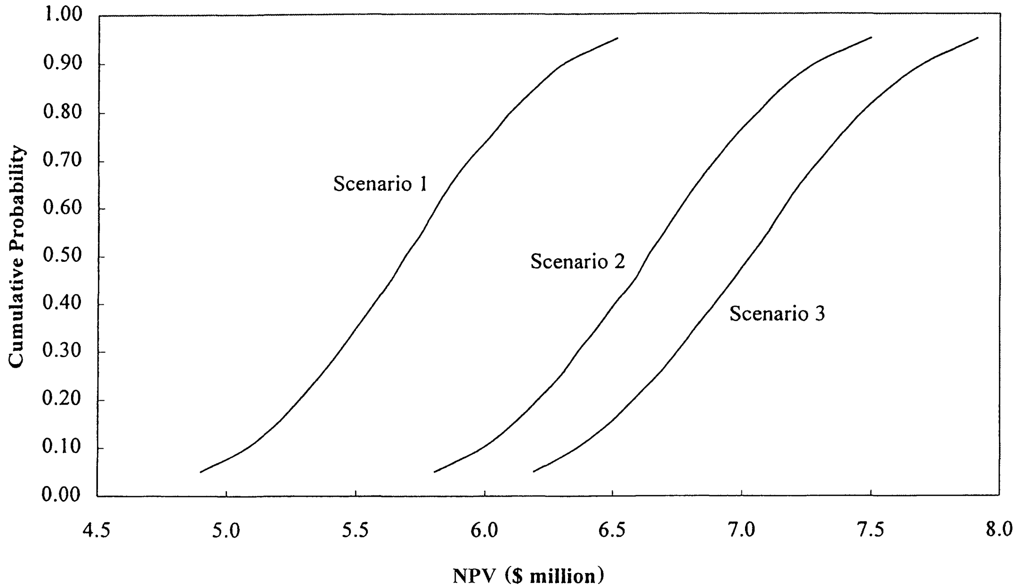

Fig. 4. Cumulative distribution functions for the alternative scenarios.

change in the optimal solution with scenario 3 remaining the preferred control option, although it was only marginally superior to scenario 2.

Seed dispersal distance: The analysis purposely used a conservative estimate of the dispersal distance, *d*. Given the uncertainty of the distance with which new infestations can occur from the original source, parameter *d* was increased from 5 to 10 km. The effect of this change was to increase the size of area *B* from 9906 to 36,271 ha. Despite the size of the external cost increasing with the increase in dispersal distance, there was no change in the relative rankings of the scenarios.

Population dispersal proportion: The population dispersal proportion parameter, *s*, was obtained from anecdotal evidence. The effect of variations in the parameter was tested arbitrarily by increasing the parameter value from 5 to 10%. This only had a marginal effect on the mean NPV for the three scenarios and did not change the preferred ranking.

Initial level of infestation: The analysis was repeated for a significantly lower level of initial infestation of serrated tussock. At an initial infestation of 20% there was little difference between scenarios 2 and 3. The larger standard deviation associated with scenario 2 suggests that scenario 3 would remain the preferred control option even for lower levels of initial infestation on area *A*.

5. Summary and discussion

An important cost associated with weeds is the external cost due to weed spread beyond farm boundaries. A stochastic simulation model was developed to determine the size of the external cost from the pasture weed serrated tussock in south-eastern Australia and to evaluate the benefits of alternative control scenarios. The model measured the rate of spread both within an area already infested with serrated tussock and an adjoining area, not previously infested, which was susceptible to weed spread from wind-borne seeds. Both areas were assumed to be in a low rainfall region and the infested area was of low soil fertility.

Three separate control scenarios for the infested area were assessed, (i) periodic use of a herbicide in a naturalised pasture system, (ii) herbicide application followed by establishment of an introduced perennial pasture and (iii), herbicide control followed by tree establishment. The scenario that resulted in maximum returns to society was the retirement of the infested area from agriculture and re-vegetation with trees, a result that held for risk attitudes ranging from risk-neutral to risk-averse. This scenario minimised the external cost from serrated tussock spreading to the adjoining area. The scenario that maximised returns to the private landholder within the infested area was control with a herbicide followed by establishment of an introduced perennial pasture. The commonly adopted control option of periodic herbicide use in a naturalised pasture system gave negative returns. The reasons for the adoption of this scenario are compulsion by legislation, and severe budget constraints combined with the high capital costs of establishing an introduced perennial pasture. Sensitivity analyses on the results indicated that they were robust for a range in variation in key parameters. The ranking of the options changed when the infested area was assumed to be of medium instead of low fertility, in which case the perennial pasture control scenario became socially optimal.

This analysis indicates that there is a clear divergence between the socially optimal form of serrated tussock control, re-vegetation with trees, and that which is privately optimal to an individual decision-maker on the infested area, introduced perennial pasture. Pursuing the privately optimal form of control will result in continued and significant external costs to neighbouring landholders. This represents an example of market failure, a necessary condition before any form of government intervention can be justified.

The policy implications of these results mainly relate to the issues of justifying some form of intervention in weed control and to the more difficult policy of acquiring marginal agricultural and environmentally sensitive land from private landholders. The first issue is more readily addressed where the external costs and market failure aspects of the problem have been established. The second issue is more difficult because of the often politically sensitive nature of land retirement. The community's acceptance of a land acquisition and rehabilitation policy is expected to be mixed. Some individuals, particularly those affected by the external costs, will support this policy while others will resist moves to retire their land from agriculture. There are few Australian precedents for such a policy and the political acceptance is unknown. An alternative and perhaps more efficient option to direct government intervention may be for landholders affected by weed spread to instigate some form of collective action at a regional or catchment level, such as purchasing or rehabilitating these marginal lands. This represents market driven policy response to the problem rather than reliance upon government intervention.

The estimated benefits for scenario 3 are considered conservative as they only consider the agricultural benefits from a reduction in the external costs of weed spread. There are a range of environmental amenity values attached to native ecosystems which are likely to be improved by the re-vegetation of agricultural lands, particularly if it involves native species. In addition, there may be benefits also associated with tree planting in terms of reduced soil loss and stream turbidity, a reduction in hydraulic loading with consequent improved dryland salinity effects, and the encouragement of a greater natural bio-diversity. Environmental benefits may also be derived from retiring marginal agricultural land and revegetation with trees due to the cessation of periodic chemical use to control serrated tussock.

The results indicate that care needs to be taken when designing an economic analysis of weed spread. Proper consideration must be given to adjoining land that is negatively impacted upon by spread from infested areas. If an analysis focuses on the benefits and costs of control solely within the infested area, then the derived preferred strategies are unlikely to closely correlate with those that are socially optimal.

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