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Economic benefits of public investment in weed management: the case of *vulpia* in south-eastern Australia's temperate pasture areas*

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The present paper reports an economic evaluation of the long-term benefits to Australia of research by the Cooperative Research Centre for Weed Management Systems (CRC) into the improved management of *vulpia*, the major annual grass weed of temperate pastures in New South Wales and Victoria. *Vulpia* reduces livestock production by competition with more desirable pasture species, by the production of low quality feed at critical times of the grazing cycle, and by injury to animals. A 20-year stochastic benefit-cost analysis indicated that reducing the impacts of *vulpia* in these pastures produced a mean net present value of $A58.3 million and a mean benefit-cost ratio of 33:1. Temperate pasture zone wool producers would capture the largest shares of these benefits, Australian consumers would gain, but wool producers in the rest of Australia would suffer welfare losses from *vulpia* reductions in the temperate pasture zones.

1. Introduction

Pasture weeds impose substantial economic costs on Australia's grazing industries. Weeds reduce pasture production, contaminate produce, injure and poison livestock, are usually costly to manage and may impose external costs through spread. As an input into the development and promotion of improved pasture weed management practices, economic evaluations of weed problems provide two levels of information. The first concerns the impacts of weeds and the benefits to producers of improved weed control in grazing systems. Producers control weeds to maintain production from pastures and may be legally required to do so. Economic estimates of the costs of weeds and the benefits of weed reduction in pastures should encourage

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improved weed management where the benefits are shown to exceed the costs. The second level of information relates to the costs of weeds to the grazing industries. Because pasture weeds are widespread, an opportunity cost of foregone production is imposed on an industry. Evaluations of these costs also indicate the potential industry benefits from improved weed management and assist in the development and promotion of weed research and extension initiatives by the livestock industries and government if it can be demonstrated that the public benefits outweigh the public costs.

From an economic perspective, the features of a plant that determine its importance as a weed are population density, impact on production, spread potential and life-cycle. Pasture weeds tend to be more difficult to evaluate economically than crop weeds because of the complex interactions between livestock and plant species. Also, there are no consistent biological properties that distinguish weeds from other pasture plants, and producers may not regard some plant species as weeds because they have some seasonal grazing value. Perennial grass weeds pose dynamic economic problems to livestock producers because of their negligible grazing values, rapid spread and competition with desirable pasture species. These weeds are most problematic where management under introduced pastures is difficult because of environmental limitations. Annual weed species may have similar characteristics but some provide periodic grazing value and are more difficult to classify as weeds in an economic sense. The economic impact of an annual weed depends on how its growth pattern corresponds to the cycles of pasture growth and the feed demands of livestock (Auld *et al*. 1979).

Pasture weeds have been a longstanding issue for public research in the temperate regions of south-eastern Australia. As a continuation of this commitment, the recently terminated Cooperative Research Centre for Weed Management Systems (CRC) conducted a major program of pasture weeds research in southern Australia between 1995 and 2002. The CRC identified several key pasture weed groups for research that included perennial and annual grasses, broadleaf weeds and thistles. The main focus of that research was to develop and extend improved practices for managing weeds in pastures. This was achieved by promoting permanent changes in the plant environment that favoured the establishment of the more desirable species at the expense of weeds (CIE 2001). Specific research issues included tactical grazing management for controlling annual grasses, the integrated management of thistles and other broadleaf weeds, and the biological control of Paterson's curse. The value of the CRC's cash and in-kind contributions to pasture weed research averaged $A1.94 million annually, and totalled $A13.64 million over the 7-year period from 1995–1996 to 2001–2002 (CIE 2001).

The annual grass weed component of the CRC's pasture weeds research is the subject of this paper. The objective is to evaluate the economic returns to the CRC's investment in research into the improved management of *vulpia* subspecies which is the major annual grass weed of pastures in the south-eastern temperate areas of Australia. Section 2 provides an overview of the *vulpia* problem in these pastures, while Section 3 outlines the methods that are used in the evaluation. The results are reported in Section 4, which is followed by a discussion of the major findings.

2. Background to the *vulpia* problem in temperate pastures

Hill *et al*. (1999) defined Australia's south-eastern temperate pasture zone (TPZ) as covering those areas with an annual rainfall greater than 600 millimetres, excluding the coasts and northern regions. On this basis, the TPZ comprises the tablelands and slopes of New South Wales, Victoria and Tasmania. The total areas of the TPZ in New South Wales and Victoria are about 7.3 and 3.8 million hectares, respectively (ABS 2000). The New South Wales TPZ contains most of the introduced perennial grass-based pastures which support half of the New South Wales livestock populations. The Victorian TPZ includes most of Victoria's introduced pastures which produce the bulk of that state's livestock commodities (table 1). Kemp and Dowling (2000) estimated that the New South Wales and Victorian TPZs are the source of 50 per cent and 40 per cent of all Australian cattle and sheep sales, respectively. In terms of Australia's specialist livestock producers 50 per cent of beef producers, 80 per cent of lamb producers and nearly 40 per cent of wool producers are located in these regions (ABARE 1998; 2000a,b). The TPZ in New South Wales and Victoria is the focus of this evaluation.

Weed surveys define the scale of weed problems and allow the assessment of their biological and economic impacts and the success of weed management programs (Lemerle 1995). Several recent surveys of parts of the TPZ have found adverse changes in the composition of many pastures towards a greater proportion of undesirable annual grasses and broadleaf weeds and an overall loss of the high value perennial grasses. Weed invasion is a major factor in the declining production from temperate pastures and weed levels are now considered to be greater than previously measured (Kemp and Dowling 2000). Dellow *et al*. (2002) found that introduced and native perennial grasses on the New South Wales tablelands formed on average one-third of pasture biomass, while low quality annual grasses comprised a further 36 per cent. Annual grasses on some sites formed up to 80 per cent of total pasture biomass and only 10 per cent of the sites contained the 50 per cent composition of introduced perennial grasses that is considered necessary to maximise pasture production. Surveys in the Victorian TPZ have produced similar results where many pastures are dominated by annual grasses. In south-west Victoria pastures contained a majority of volunteer annual

Table 1 Summary of ABS data for the New South Wales and Victorian temperate pasture zones†

	Introduced pastures‡ ('000 ha)	Sheep and lambs (millions)	Lambs marked (millions)	Wool Output (kt.)	Beef cattle (millions)
New South Wales	1764	42.4	14.8	193.3	6.1
New South Wales TPZ	1392	22.9	7.3	95.9	3.5
New South Wales proportion in TPZ (%)	79	54.0	49.3	49.6	57.3
Victoria	2109	22.3	7.6	103.4	2.6
Victorian TPZ	1895	18.7	6.2	86.2	2.5
Victorian proportion in TPZ (%)	90	83.8	81.5	83.3	96.1
Australia	5076	120.2	40.4	572.4	23.8
New South Wales TPZ to Australia (%)	27	19.0	18.0	16.7	14.7
Victorian TPZ to Australia (%)	40	15.5	15.3	15.0	10.5

† Australian Bureau of Statistics data for 1996–1997; ‡ introduced perennial grasses and legumes.
TPZ, temperate pasture zone.

grasses and comprised only 15 per cent of introduced grasses (Quigley *et al.* 1993). Managing weeds has become the major problem faced by livestock producers in maintaining temperate pasture production in south-eastern Australia (Reeve *et al.* 2000).

Vulpia are naturalised species of Mediterranean origin that reduce livestock production by competing with more desirable pastures and by producing lower quality feed. *Vulpia* seeds also injure animals and contaminate wool and skins. While *vulpia* has some grazing value at times of the year, it displaces more productive pasture species and does not compensate for feed losses when livestock demands are greatest and the perennial grass content of the pasture is low (Dowling 1996). *Vulpia* is very persistent in all temperate pastures and is difficult to manage. Typical *vulpia* contents in temperate pastures that impact adversely on pasture production are between 30 and 40 per cent of pasture biomass. There are no data on the area distribution of *vulpia* because it is commonly found in all types of pastures. However, recent surveys reveal that *vulpia* infestations in many temperate pastures are at levels that significantly reduce the availability of the desirable species.

The research problem addressed in the present evaluation is the measurement of the long-term net benefits from the CRC's research into the management of *vulpia* in the TPZ. This requires the definition of appropriate with-research and without-research scenarios. Alston *et al.* (1995) noted that defining relevant research scenarios is potentially one of the most useful parts of the research evaluation process but it is also often difficult because many evaluations are concerned with on-going rather than new programs. They further noted that in this process the ongoing with-research scenario usually implies a baseline that presumes an indefinite continuation of the research program, whereas the without-research scenario implies that none of the baseline research has been undertaken. For that reason, that definition of a without-research scenario may have limited relevance to many agricultural research programs since there has usually been some past research investment that helps to establish the baseline, for example, improved plant varieties usually incorporate improvements that resulted from earlier programs. The importance of being able to clearly define relevant research evaluation scenarios has been recently emphasised by Marshall and Brennan (2001).

Other scenarios were proposed that embody different assumptions about the baseline. One of these scenarios is considered relevant to this weed research evaluation; that the with-CRC research scenario involves a continuation of a research investment while the without-CRC research scenario represents a funding reduction. The latter scenario recognises that there had been investment in *vulpia* research prior to the advent of the CRC.

Vulpia management research has been undertaken by Australian state and federal government institutions over many years and thus the CRC is not fully responsible for the *vulpia* management technology that is the subject of the present evaluation. Rather, its activities enabled the development and extension of this technology to be expedited and to produce research outputs that capitalised on the findings of the past research. The with-CRC research scenario is defined as covering the research that was undertaken during the period of the CRC. This program was an important addition to the scale of *vulpia* research and was the major project on this issue in the TPZ over the past 10 years. The alternate without-CRC research scenario was assumed to have a research budget that was reduced by the amount of the CRC's project funding.

3. Methods

3.1 Overview

The first task in measuring the CRC research benefits was to determine the extent of the *vulpia* problem and the outcome expectations of the researchers. While *vulpia* is manageable at relatively low levels, it becomes an economic problem at higher pasture contents. Content levels of greater than 30 per cent *vulpia* in TPZ pastures are common. On the CRC's experimental sites, the initial *vulpia* content of 2.5 tonnes per hectare represented nearly 50 per cent of pasture biomass, while the average *vulpia* content in pastures throughout the district was about 30 per cent (Dowling 1997). The baseline *vulpia* level that typified the problem was obtained from a detailed weed survey of the New South Wales tablelands and was set at 36 per cent of the pasture biomass (Dellow *et al*. 2002).

In weed technology evaluations, benefits are not only influenced by the losses per unit area caused by weeds, but also by the level of adoption of the research outcomes. When combined with seasonal variations these factors introduce uncertainty into the evaluation process which can be assessed using stochastic methods where the main parameters, such as supply shifts and research outcome adoption levels, are set as random variables. To account for uncertainty in the estimation of likely research benefits and the realisation of these benefits over time by producers, a stochastic Monte Carlo approach is used to undertake the benefit-cost analysis. This approach is similar to that of Zhao *et al*. (2000) who used subjective probability distributions for measuring the economic surplus change from technical change in the Australian wool industry.

A triangular probability distribution was chosen to represent the random variables that are the supply shift, adoption ceiling and lag in adoption.

This continuous probability distribution is useful for situations when actual data are absent and parameter estimates need to be elicited, as in the *vulpia* researchers' case. The triangular distribution is specified with three parameters, a minimum, most likely and maximum. The direction of the 'skew' of this distribution is set by the size of the most likely value relative to the minimum and maximum. The probability of occurrence of the maximum and minimum values is zero (Palisade 2000).

The *vulpia* research program demonstrated that under strategies involving tactical grazing and fertiliser use, *vulpia* could be reduced to less than 15 per cent of pasture biomass and maintained at that level with good grazing management (Dowling 1997). Since these results were derived under experimental rather than field conditions, a reduction in *vulpia* biomass from the baseline 36 per cent to 15 per cent was set as the maximum benefit that could be achieved from the CRC *vulpia* research. This assumption recognises that while problem *vulpia* infestations can be reduced to manageable levels, the reduced weed level has to be maintained to prevent large infestations from rapidly re-emerging.

The change in *vulpia* biomass for the two scenarios was elicited from the *vulpia* researchers. For the with-CRC research scenario the maximum research benefit was a reduction in *vulpia* from 36 per cent to 15 per cent of biomass, the most likely was to 20 per cent, and the minimum was a reduction to 25 per cent. The without-CRC research scenario involved a maximum benefit of 20 per cent *vulpia* biomass (from 36 per cent), most likely of 25 per cent, and a minimum of 35 per cent biomass. The actual supply shifts associated with these *vulpia* levels were calculated from a grazing simulation model and were defined as the triangular probability distribution parameters (table 2).

Table 2 Probability distribution parameters

	Triangular distribution parameters		
	Maximum	Most likely	Minimum
Wool supply shift $K^\dagger$			
with-CRC research	0.26	0.13	0.03
without-CRC research	0.13	0.06	0.002
Adoption ceiling (%)			
with-CRC research	60	35	25
without-CRC research	50	30	20
Adoption lag (years)			
with-CRC research	7	4	2
without-CRC research	10	5	3

† Reduction in production cost (cents/kg) as a proportion of product price (cents/kg).
CRC, Cooperative Research Centre for Weed Management Systems.

The difference between the simulated benefits of both scenarios thus represents the benefits from *vulpia* research that can be attributed to the CRC. Simulating the respective benefits from these two scenarios provides a transparent means of determining the expected payoffs to the alternate *vulpia* research programs. The estimates for the *vulpia* biomass reduction were used to calculate the changes in the costs of growing wool (supply shifts) which are crucial determinants of the total research benefits (Alston *et al*. 1995, p. 327). The with-CRC and without-CRC research scenarios incorporate these estimates.

Another consideration was the anticipated level of adoption of the research outcomes. Because this parameter was not measurable during the period of the research, adoption values were elicited from the researchers and were also represented by a triangular probability distribution (table 2). These values represented the expected uptake of the research outcomes by the *vulpia*-affected producers and applied to both the with-CRC and without-CRC research scenarios. The lag before the adoption of the technology was also specified as a random variable to reflect uncertainty in the adoption process and again applied to both scenarios.

A further dimension of the evaluation is the potential degree of correlation in the input distributions used for the two *vulpia* research scenarios. The scenarios could be highly correlated as it is possible that in the absence of the CRC input, a level of ongoing *vulpia* research would be undertaken by the same researchers and institutions. The importance of this correlation is that it influences the shapes and the proximity of the probability distributions for the two research scenarios. A zero correlation implies that the distributions are fully independent, while a high correlation narrows the distribution spread and indicates that the with-CRC research scenario has a strong link to the other *vulpia* research that is represented by the without-CRC research scenario.

There was no information to indicate the possible degree of this correlation between the benefits of the scenarios. Consequently, a case study approach was taken to evaluate the implication of assuming independence in the research benefits against a case where the benefits are highly correlated. A rank-order correlation coefficient (C) was used to reflect the degree of correlation between the input distributions. The coefficient is a value between 1 and −1, and represents the desired degree of correlation between two variables during sampling. Coefficient values of $C = 0$ and $C = 0.8$ were used for the two case studies. The latter correlation value is considered to be the more realistic since the same researchers were involved in both programs.

The methods adopted for research benefit estimation follow the proposition that weeds such as *vulpia* impose costs on livestock producers and industries, and that weed reductions through more effective management become benefits. On this basis, three elements of the economic modelling system described in Vere, Jones and Griffith (1997) were used to evaluate the costs of *vulpia*: (i) a grazing systems simulation model (GSM) of temperate pasture systems; (ii) a regionally disaggregated economic surplus model; and (iii) a benefit-cost analysis (BCA) model. The links between these components are that the GSM establishes the effects of a weed in a production system and the output and revenue changes from improved weed management. Industry supply responses are then estimated by aggregating the production system responses under a given level of weed management technology adoption across an industry. With estimates of the supply and demand curves, the type of supply shift, and the relationship between producer and consumer prices, the value of the welfare changes from this activity are calculated using the economic surplus model. The BCA then enables the benefit-cost criteria of these changes to be calculated. The results of applying this modelling system help to determine whether public investment in the development of improved pasture weed management is likely to be profitable.

3.2 Grazing systems simulation model

The GSM was used to determine the optimal output and revenue differences for alternative levels of weed composition within a pasture. Given that weeds restrict livestock production by reducing feed availability, the model evaluates weed impacts in terms of the opportunity costs of livestock production foregone. Weeds are undesirable because they take up an ecological space that could be occupied by a more valuable plant. The model considers varying proportions of the ecological groups, ranging from high levels of perennial grasses to high levels of *vulpia* and other weeds. Variations in soil fertility and seasonal conditions are reflected in differences in the calculation of daily pasture growth rates and potential biomass accumulation of each species functional group. The GSM is a daily time-step simulation model which calculates the growth of individual pasture species and livestock feed demands. This model is fully described in Jones, Dowling and Michalk (unpublished); a brief description is given as follows.

The objective function (π) is to determine the net annual return from a prespecified mix of pasture species and livestock stocking rate:

$$\pi = LR - LC - SFC - PVC - FC - HC \qquad (1)$$

where π is net return (\$A per hectare), LR is livestock revenue, LC are livestock production costs, SFC are supplementary feed costs, PVC are pasture variable costs, *FC* are the costs of fertiliser and application, and *HC* are herbicide costs. The values of *FC* and *HC* are set to zero and livestock revenue is derived from the function:

$$LR = f(SR, WC, WPRICE, LSALE, LPRICE) \quad (2)$$

where *SR* is livestock stocking rate (head per hectare), *WC* is wool cut (kg per head), *WPRICE* is the average price of wool ($A per kg), *LSALE* is the number of culled livestock and *LPRICE* is the average price of culled livestock ($A per head). The value of wool cut is influenced by the amount of protein in a sheep's diet, which in the model is a function of the pasture species composition:

$$WC = f(PG, LG) \quad (3)$$

where *PG* and *LG* are the compositions of the perennial grass and legume species. Livestock costs are given as:

$$LC = f(SR, LVCOST, RP, RC) \quad (4)$$

where *LVCOST* is the variable husbandry costs of livestock ($A per head), *RP* and *RC* are replacements and their costs ($A per head). *RP* is determined by the flock mortality rate, which is influenced by the species composition and seasonal conditions.

The cost of supplementary feeding is a function of the amount of grain fed to livestock (tonnes) and the cost of grain ($A per tonne). The daily amount of grain fed is determined from an energy balance equation:

$$MEG = TLME - MEP \quad (5)$$

where *MEG* is the daily metabolisable energy provided by supplementary grain (MJ ME per hectare), *TLME* is the total daily livestock metabolisable energy requirements, and *MEP* is the total metabolisable energy supplied by the pasture. This results in grain being fed to livestock only when there is a deficit in feed energy supplied from pasture. The value of *MEP* is determined by the biomass (kg per hectare) of each species present in the pasture and the metabolisable energy of that species for a given day (MJ ME per kg):

$$MEP = f\left(\sum_{i=1}^{6} W_i ME_i\right) \quad (6)$$

where W_i is the biomass of species i and ME_i is the daily average metabolisable energy supplied by the ith species. The model further divides the biomass and metabolisable energy for each species into five digestibility pools. The composition of the individual species within a grazing system has significant implications for pasture biomass, the feed energy supplied, livestock production and, consequently, financial returns. The GSM can specify up to six ecological functional species groups within a grazing system; introduced perennial grasses such as phalaris and cocksfoot, native winter growing perennial grasses such as *microlaena* and *danthonia* spp., native summer growing perennial grasses such as kangaroo grass and red grass, legumes such as subterranean clover, annual grasses such as *vulpia*, and broadleaf weeds such as Paterson's curse and thistles. The contribution of each species to total pasture biomass is derived from a logistic growth rate equation:

$$\frac{dW_i}{dt} = [S_i \times GI_t \times W_t(WMAX_i - W_t)]C_i \tag{7}$$

where dW_i/dt is the daily growth of species i (kg per hectare), S_i is a species specific constant, GI_t is a daily growth index, W_t is the pasture biomass (kg per hectare), $WMAX_i$ is an asymptote for the biomass of species i (kg per hectare), and C_i is the composition of the species. The growth index involves the transformation of the non-linear responses of plants to the major light, thermal and water regimes into dimensionless ratios with a scale of zero to unity (Fitzpatrick and Nix 1970).

The GSM was used to calculate the wool supply shifts from improved *vulpia* management. This involved adjusting the composition of the pasture species to represent the pasture *vulpia* contents that define the with-CRC and without-CRC research scenarios. Any additional costs incurred in doing this were also measured. The model was then solved to calculate the reductions in the cost per kilogram of wool production that were attributable to the *vulpia* research. When expressed as a proportion of the commodity price (P_0), this procedure estimated the proportional supply shift parameters (K) for a Merino wether wool-growing enterprise (table 2). In this weed control instance, the supply shift represents a research-induced cost saving.

3.3 Economic surplus model

The second element of the economic modelling system is an economic surplus model of the type that has been commonly used in evaluating the welfare effects of production constraints such as weeds, or of production-increasing technologies such as improved weed management. Welfare changes are estimated from the changes in prices and quantities that arise from the common assumption of a parallel supply shift, and are distributed between producers and consumers according to the supply and demand elasticities. In the case of an outward supply shift, consumers always benefit because of the increased supply at a lower price and gain most when supply is elastic and demand is inelastic. The net welfare effect on producers depends on whether the increased industry revenue at the higher production compensates for any price decrease. Producers gain most under an inelastic supply and an elastic demand. With pasture weeds, the latter elasticity conditions relate to most of Australia's major livestock commodities in the shorter term (Griffith *et al*. 2001a,b).

A regionally disaggregated economic surplus model was used to accommodate the regional context of the *vulpia* problem and its management technology. Lindner and Jarrett (1978) recognised that many agricultural technologies were location specific. If the evaluation of the impact of the technology was disaggregated into relatively homogenous production regions, a linear parallel supply shift would usually give a good approximation of the benefits. Davis (1992) noted that most of these evaluations focused on aggregate (usually national) supply on the implicit assumption that the technology was uniformly or proportionally applicable to all regions of an industry and that the cost structures of all producers were the same. This was considered to be inconsistent with the differences in the resources and environments that typically exist in agricultural production systems and that a model with a regionally disaggregated supply was necessary to represent these differences. A similar approach had earlier been used by Edwards and Freebairn (1982) to evaluate the problem of the major perennial grass weed serrated tussock in New South Wales.

Alston *et al*. (1995) describe several versions of the disaggregated economic surplus model that capture the regional and national implications of technology adoption. One model represents a large open economy with price spillovers to other areas because the technology adopter is a sufficiently large exporter to cause price effects in the other markets, but no technology spillovers because of the regional specificity of the technology. The model has an excess supply and demand specification and applies equally to between-region or between-country analyses. Where two regions A and B are considered, the changes in economic surplus from technology adoption are represented by a parallel supply shift in both regions. Technology adoption in region A results in an increased supply in that region, and lowers price in both regions. Consumers in both regions gain from the increased supply and the lower price, producers in region A derive a net gain from the lower production costs (outward supply shift), while producers in region B lose from the reduced price for their unchanged supply.

However, the net welfare effects in region B may be positive since consumer gains may exceed producer losses. The overall welfare effect is that both regions benefit from technology adoption in region A. This model is a realistic scenario for evaluating *vulpia* management in Australia's temperate pastures since the *vulpia* management technology is regionally specific, the TPZ is a large part of the national sheep and wool industries, and there is a likelihood of price spillovers between the regions. Improved *vulpia* management provides an example of a price spillover that benefits producers and consumers in the technology adopting region, and consumers in the nonadopting region. The technology does not benefit producers in the non-adopting region who are unable to adopt the technology and so lower their production costs.

The formulae for calculating the economic surplus changes using this model for the two regions TPZ and the rest of Australia (ROA) are given in Alston *et al.* (1995, p. 407):

$$\Delta CS_{TPZ} = P_0 Q_0 Z(1 + 0.5Z\eta_{TPZ}) \tag{8}$$

$$\Delta PS_{TPZ} = P_0 Q_0 (K - Z)(1 + 0.5Z\varepsilon_{TPZ}) \tag{9}$$

$$\Delta CS_{ROA} = P_0 Q_0 Z(1 + 0.5Z\eta_{ROA}) \tag{10}$$

$$\Delta PS_{ROA} = -P_0 Q_0 Z(1 + 0.5Z\varepsilon_{ROA}) \tag{11}$$

where *CS* is consumer surplus, *PS* is producer surplus, *TPZ* is the temperate pasture zone, *ROA* is the rest of Australia, P_0 and Q_0 are the respective equilibrium farm and retail prices and production and consumption quantities, Z is the relative price change resulting in the market following adjustment to the new equilibrium, K is the initial supply shift and ε and η are the price elasticities of supply and demand.

These equations represent two regions but can be expanded to represent any number of regions, including international regions. Both the annual costs of *vulpia* and the benefits of its improved management were evaluated using this model. Wool elasticity values were derived from Griffith *et al.* (2001a,b). All elasticity values were for the medium term and were 0.3 and 1.4 for the TPZ and Australian wool supply, respectively and −0.8 for the Australian wool demand (table 3). No regional wool consumption was considered. Values of the supply shifts were calculated using the GSM, while the equilibrium wool production level in the TPZ was sourced from the Australian Bureau of Statistics (2000). Australian values for these variables were the averages of the last five years reported in ABARE (2001).

Table 3 Parameter values used in economic surplus calculations

Parameter	Value/unit	Source
TPZ wool production (kt)	182	ABS (2000)
ROA wool production (kt)	580	ABS (2000)
Australian wool consumption (kt)	18	ABARE (2001)
TPZ wool supply elasticity	0.3	Griffith *et al*. (2001b)
Australian wool supply elasticity	1.4	Griffith *et al*. (2001b)
Australian wool demand elasticity	−0.8	Griffith *et al*. (2001a)
Average farm wool price (c/kg)	667	ABARE (2001)
Wool production costs (c/kg):		
15% *vulpia*	287.4	GSM
20% *vulpia*	374.4	GSM
25% *vulpia*	419.4	GSM
30% *vulpia*	439.0	GSM
35% *vulpia*	459.5	GSM
36% *vulpia*	460.7	GSM

GSM, grazing systems simulation model; ROA, rest of Australia; TPZ, temperate pasture zone.

3.4 Benefit-cost analysis model

Benefit-cost analysis is the third element of the modelling system. A Monte Carlo analysis is used to assess the benefits of the CRC *vulpia* research and calculated probability distributions of net present value (NPV) and benefit-cost ratio (BCR) for a 20-year simulation period commencing in 2003. The stochastic analysis involved 5000 iterations of the 20-year simulation using a Latin Hypercube sampling procedure to draw random values from the input distributions previously described. The discount rate (r) was set at 5 per cent. The NPV was calculated from the net benefits of the CRC research (NB):

$$NPV = \sum_{t=1}^{20} \left(\frac{NB_t}{(1 + r)^t} \right) \tag{12}$$

The net benefits were derived from the difference in the annual benefits (B) of the with-CRC and without-CRC research benefits, less the CRC project costs. The annual research benefits are a function of the total research benefit and the annual rate of adoption (A):

$$B_{1t} = RB_{1t} \times A_{1t} \tag{13}$$

$$B_{2t} = RB_{2t} \times A_{2t} \tag{14}$$

$$NB_t = (B_{1t} - B_{2t}) - (PC_t + EC_t) \tag{15}$$

where B_1 is the with-CRC annual research benefit, B_2 is the without-CRC annual research benefit, RB_1 is the total with-CRC research benefit estimated from the economic surplus model, RB_2 is the total without-CRC research benefit, A_1 is the annual rate of adoption of the with-CRC research, A_2 is the annual rate of adoption of the without-CRC research, and PC and EC are the initial project costs and annual extension costs, respectively. The costs were estimated from the CRC financial statements to be \$A2.1 million in year 0 for the project costs, and \$A100 000 annually for the extension costs. The annual rate of adoption (A_t) is a function of the ceiling level of adoption (CA) and the rate of adoption in the previous year and is calculated from the following logistic equation. The lag in adoption parameter determines in which year of the simulation period the adoption rate equation commences:

$$A_t = A_{t-1} + [A_{t-1}(CA - A_{t-1})]. \tag{16}$$

4. Results

The summary statistics of the stochastic simulation modelling are given in table 4 for the independent research scenarios (i.e., $C = 0$) and in table 5 for

Table 4 Summary statistics from Monte Carlo simulation for estimation of benefits from CRC vulpia research for the case of research independence ($C = 0.0$)

	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation
ΔES (\$Am)					
with CRC	26.0	198.8	107.7	35.6	33.1
without CRC	1.8	99.3	49.4	20.0	40.5
net CRC benefit	−62.2	185.3	58.3	40.8	70.0
ΔPS (\$Am)					
TPZ with CRC	36.9	282.0	153.8	51.0	33.1
TPZ without CRC	2.8	140.1	70.4	28.5	40.5
ROA with CRC	−87.9	−11.4	−47.8	15.9	33.3
ROA without CRC	−43.5	−0.8	−21.7	8.8	40.6
ΔCS (\$Am)					
with CRC	0.4	3.2	1.7	0.6	33.3
without CRC	0.0	1.6	0.8	0.3	40.5
Benefit-cost analysis					
NPV (\$Am)	−89.8	452.7	95.7	69.6	72.7
BCR	−28.6	150.2	32.6	22.9	70.4

BCR, benefit-cost ratio; *C*, rank order correlation coefficient; CRC, Cooperative Research Centre for Weed Management Systems; CS, consumer surplus; ES, economic surplus; NPV, net present value; PS, producer surplus; ROA, rest of Australia; TPZ, temperate pasture zone.

Table 5 Summary statistics from Monte Carlo simulation for estimation of benefits from CRC vulpia research for the case of research correlation ($C = 0.8$)

	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation
ΔES ($Am)					
with CRC	26.4	198.8	107.7	35.6	33.1
without CRC	2.3	99.3	49.4	20.0	40.5
net CRC benefit	–2.2	130.5	58.3	23.1	39.7
ΔPS ($Am)					
TPZ with CRC	36.2	281.8	153.8	51.0	33.1
TPZ without CRC	3.0	140.2	70.4	28.5	40.5
ROA with CRC	–87.9	–11.4	–47.8	15.9	33.3
ROA without CRC	–43.6	–0.7	–21.7	8.8	40.6
ΔCS ($Am)					
with CRC	0.4	3.2	1.7	0.6	33.3
without CRC	0.0	1.6	0.8	0.3	40.5
Benefit-cost analysis					
NPV ($Am)	3.2	406.8	95.9	53.8	56.1
BCR	2.1	135.1	32.6	17.7	54.3

BCR, benefit-cost ratio; *C*, rank order correlation coefficient; CRC, Cooperative Research Centre for Weed Management Systems; CS, consumer surplus; ES, economic surplus; NPV, net present value; PS, producer surplus; ROA, rest of Australia; TPZ, temperate pasture zone.

the case where the research scenarios are highly correlated (i.e., $C = 0.8$). The cumulative distribution functions (CDF) for selected outputs of the modelling process are given in figure 1.

The results in table 4 indicate that *vulpia* research has the potential to generate high levels of economic benefits over the range of expectations for the research and the adoption of its outcomes. For the with-CRC research scenario, the mean increase in economic surplus was $A107.7 million, while for the without-CRC scenario there was a $A49.4 million increase in economic surplus. The net benefit from the CRC *vulpia* research was derived from the stochastic modelling process and, consequently, is not the arithmetic difference between the with-CRC and without-CRC values. The net CRC research benefit result is represented by a probability distribution with a mean of $A58.3 million, and maximum and minimum values of $A185.3 and –$A62.2 million, respectively.

The benefits to wool producers from *vulpia* research are disaggregated into the two regions TPZ and ROA. Producers in TPZ gain from *vulpia* research and producers in the ROA lose economic surplus because of the reduced wool price. The effect of the with-CRC research is to increase the gains to TPZ (from mean $A70.4 million to $A153.8 million) and to increase the losses to ROA (from mean –$A21.7 million to –$A47.8 million).

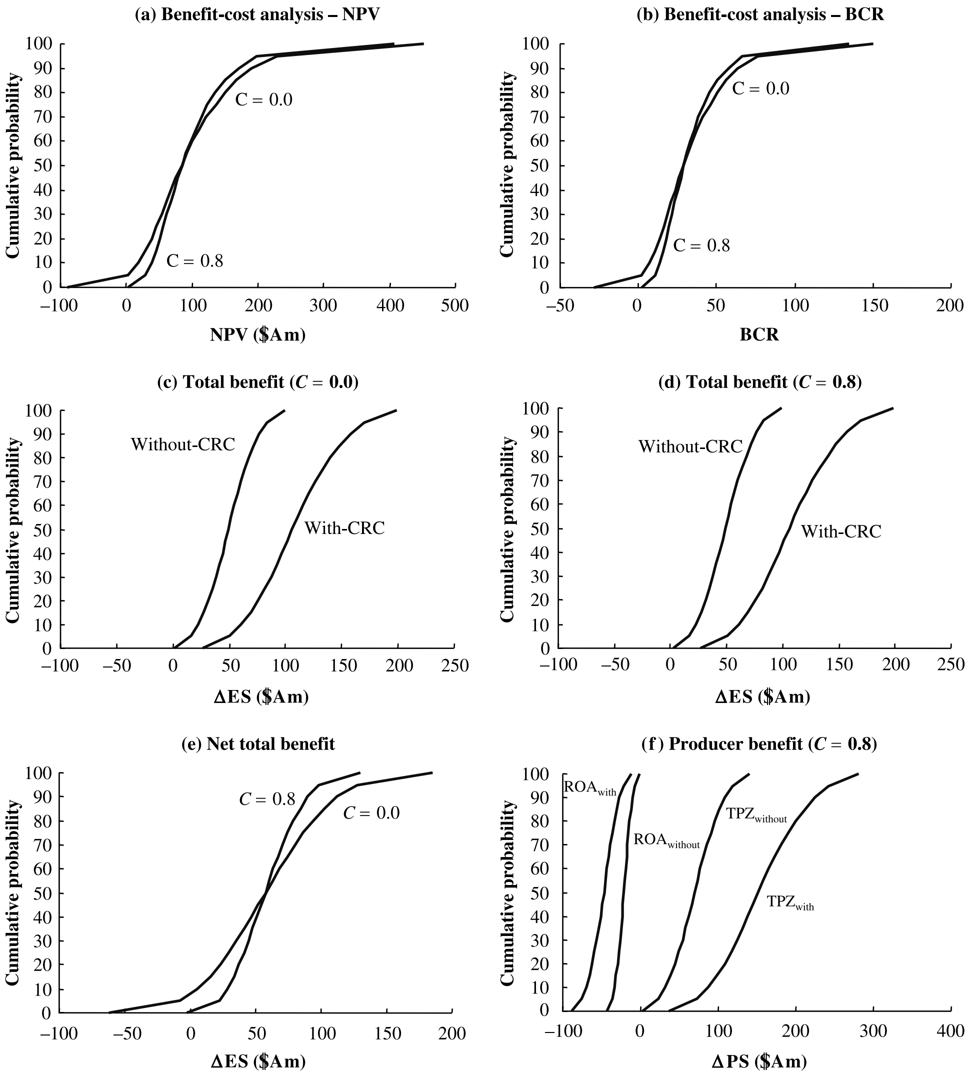

Figure 1 Cumulative distribution functions for the net present value (NPV), benefit-cost ratio (BCR), economic surplus change (ΔES) and producers' surplus change (ΔPS) of *vulpia* research. *C*, rank-order correlation coefficient; ROA, rest of Australia; TPZ, temperate pasture zone.

The gains to consumers from *vulpia* research were relatively small for both scenarios.

The benefit-cost analysis for the research independent case indicated that large economic benefits were obtained from the CRC's *vulpia* research with a mean NPV of $A95.7 million and a mean BCR of 32.6. However, there was substantial variability in the results of the benefit-cost analysis with the

NPV ranging from a minimum of –\$A89.8 million to a maximum of \$A452.7 million with a coefficient of variation of 72.7.

The effect of allowing for correlation between the two *vulpia* research scenarios is indicated in table 5. Including a rank-order correlation coefficient of 0.8 only had an impact on the net CRC research benefit and the results of the benefit-cost analysis. The with-CRC and without-CRC scenario results for economic surplus, producer surplus and consumer surplus change were unaffected.

For the net CRC research benefit, although the mean remained identical at \$A58.3 million, the variability around the mean was substantially reduced. The range in values was from a minimum of –\$A2.2 million to a maximum of \$A130.5 million, and the coefficient of variation declined from 70.0 to 39.7. The reduction in the relative variability of the net research benefit had a flow-on effect upon the derived values for the NPV and BCR, where the range in values and the coefficient of variation were similarly substantially reduced.

The CDF for the economic surplus and benefit-cost analyses illustrate these results (figure 1). The NPV and BCR CDF in figure 1(a) and figure 1(b) indicate that, although there are differences in the distributions for the two correlation case studies, there is a high probability of large economic benefits from the CRC's *vulpia* research. In the case of $C = 0.8$ there is a 90 per cent probability that the NPV would exceed \$A40 million and the BCR exceed 15 based on the 10th percentile results.

For the two correlation cases, the results in figure 1(c) and figure 1(d) show that there is no difference in the CDF for economic surplus change. Consequently, the effect of considering correlation in the two research scenarios is to influence the distribution of the net benefits, not the absolute level of economic surplus change. This result is illustrated in figure 1(e) which shows how the variability in the distribution of the net economic surplus change is reduced when the two research scenarios are highly correlated. An important result is that when the research benefits are highly correlated there a very low probability of a negative net CRC benefit. However, in the case of research independence there is around a seven per cent probability that the net CRC benefit is less than zero.

The effect on producer surplus change in the two regions for with-CRC and without-CRC *vulpia* research is illustrated in figure 1(f) which shows the relative producer surplus changes from *vulpia* research for TPZ and ROA wool producers. The effect of the CRC is to magnify these gains and losses.

5. Discussion

The present paper presents estimates of the potential long-term benefits from a public program of research into the improved management of the pasture weed *vulpia*. *Vulpia* is the major annual grass weed of temperate pastures in south-eastern Australia. When measured in terms of the opportunity costs of production foregone from reduced pasture availability, *vulpia* infestations in pastures can potentially cause large annual costs to wool producers in the temperate pasture areas of New South Wales and Victoria. The potential benefits from reducing *vulpia* are equivalent to the value of the opportunity cost reductions and are the total benefits that could result from research into reducing this weed. Because it has not been possible to quantify the total costs of all research that has been made into the *vulpia* problem by Australian research institutions over the years, the known research costs of one such institution, the Cooperative Research Centre for Weed Management Systems, for a specific period, have been used in lieu. The benefits that have been defined are considered to be specific to that *vulpia* research program where its major contribution has been to expedite the development and release of improved *vulpia* management technologies.

The principle of pasture weed management is to reduce the space available for weeds by maximising the ground cover with desirable species. This reduces the potential establishment of the non-desirable species. Management involves replacement of weeds with persistent perennial grasses with the support of nitrogen-fixing legumes (Dowling 1996). This necessitates establishing pastures under cultivation or by aerial methods, the use of herbicides and fertilisers, and strategic stocking in accordance with the pasture growth cycles to maximise pasture competition. These results indicate the potential for large long-term economic benefits from more effective *vulpia* management by using these methods. The 20-year stochastic NPV benefit estimates include the expected welfare gains to TPZ wool producers, all Australian wool consumers and welfare losses to wool producers outside the TPZ.

The results are consistent with the theory of a spatially disaggregated economic surplus model in which regionally specific technology adoption in one region benefits local producers, but those in other regions suffer welfare losses from price spillovers. Although the actual values are not comparable, these results are similar to the general findings of Edwards and Freebairn (1982) on serrated tussock. Reducing pasture weeds in one region results in welfare gains to all consumers and regional producers, producers in other regions lose, and there is a net gain to Australia from improved pasture weed management.

An issue that arises in considering these results is the extent to which they are conditioned by the assumptions that have been made. Estimates of economic welfare or surplus change have often been sensitised on the basis of important parameters such as the supply shift. This problem was addressed by the use of a Monte Carlo simulation approach that incorporates a probability distribution of the expected outcomes and adoption of the *vulpia* management research. This has provided a more rigorous means of recognising that both the research outcomes and the benefit estimates are subject to uncertainty.

Elasticities are also often varied to sensitise the distribution of benefits between producers and consumers. Australian wool supply elasticities are typically price inelastic in the short term. Griffith *et al.* (2001b) reviewed 12 studies that reported Australian wool supply elasticities using different estimation methods and time periods. Of 40 reported wool supply elasticities, 31 had values less than 0.5. Wool demand elasticities are generally larger in Australia and very large internationally, for example, the excess demand elasticity of −3.4 estimated by Hill *et al.* (1996). The consistency of these estimates suggests that there would be little point in further sensitising these benefit-cost estimates for *vulpia* research using different elasticity values. A more elastic wool demand would still direct the largest benefit share to TPZ producers and larger losses to other producers, with corresponding reductions in consumer benefits. Also, the economic surplus formulae relate to single commodities (wool) and do not take account of cross-commodity effects. Most production systems in the TPZ incorporate several forms of livestock production, usually with prime lambs and beef cattle, and so the benefits of improved *vulpia* management that have been attributed to the wool industry will be shared with the other livestock industries.

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