An Economic Evaluation of Research into the Improved Management of the Annual Grass Weed *Vulpia* in Temperate Pastures in South-Eastern Australia

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Abstract: NSW Agriculture has a history of research investment in managing weed problems in the temperate pasture areas. One focus of that research has been on the development of improved management practices for the major annual grass weed *vulpia*. Recent surveys have found that weeds comprised up to 80% of pasture biomass in some temperate areas and that typical *vulpia* contents are between 30 and 40% of pasture biomass. Temperate pasture degradation is recognised as being a major contributor to the wider environmental problems of soil erosion, salinity and acidity. This evaluation related to a project (1996-2002) that focussed on the *vulpia* problem in the New South Wales temperate pasture areas. The benefits of that research were measured as the difference in the economic returns from the project (the *with-research scenario*) and those that would have resulted if the project had not been initiated (the w*ithout-research scenario*). The results indicated high levels of economic benefits from the *vulpia* project. The annual net project benefit had a mean value of $58 million. The benefit-cost analysis generated a mean NPV of $196.9 million and a mean BCR of 22.2. These results demonstrate that research by NSW Agriculture into the improved management of *vulpia* has the potential to generate substantial long-term economic benefits. Other socio-economic aspects of the results showed that wool producers outside the New South Wales temperate areas lost economic surplus (from a mean -$21.7 million to -$47.8 million) because they were unable to adopt the cost-reducing technology and faced a reduced wool price. All wool consumers gained from *vulpia* research because of expanded wool production and lower wool prices. Improved *vulpia* management is also considered to produce important environmental benefits by encouraging a greater use of deep-rooted perennial grasses and the beneficial effects of these on mitigating soil problems and reducing water table discharges.

Keywords: benefit cost analysis; research evaluation; annual grass weeds; *vulpia*

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Executive Summary

NSW Agriculture has a history of research investment in managing weed problems in the temperate pasture areas. One focus of that research has been on the development of improved management practices for the major annual grass weed *vulpia*. Recent surveys have found that weeds comprised up to 80% of pasture biomass in some temperate areas and that typical *vulpia* contents are between 30 and 40% of pasture biomass. Livestock producers perceive weeds to be the major symptom of pasture decline in this part of the state. Temperate pasture degradation is recognised as being a major contributor to the wider environmental problems of soil erosion, salinity and acidity.

This evaluation related to an industry funded project that ran between 1996-2002 (DAN158) that focussed on the *vulpia* problem in the New South Wales temperate pasture areas. The benefits of that research were measured as the difference in the economic returns from the project (the *with-research scenario*) and those that would have resulted if the project had not been initiated (the w*ithout-research scenario*). The latter recognises that there has been a past investment in *vulpia* research by NSW Agriculture and other organisations.

Approach to the evaluation

Vulpia and other weeds impose costs on livestock producers and their industries, and economic benefits result from improved management that reduces weeds. The main task was to determine the extent to which the project was expected to reduce the *vulpia* problem. The baseline that typified the problem was set at 36% *vulpia* composition after recent weed survey results. Under strategies involving tactical grazing and fertiliser use, the *vulpia* content could be reduced to less than 15% and maintained there with good grazing management. This was the maximum benefit that could be achieved from the research. To recognise the uncertainty that is associated with the estimation of the benefits and their realisation by producers, minimum (25%), most likely (20%) and maximum (15%) benefit values were elicited from the project staff for the *with-research* scenario. The *without-research* scenario involved a maximum benefit of 20% *vulpia* biomass (from 36%), most likely of 25%, and a minimum of 35% biomass. The difference between the simulated benefits of both scenarios represented the benefits from *vulpia* research that can be attributed to the DAN158 project. Adoption values were also elicited and simulated as a probability distribution, with the most likely level of adoption being 35% of the wool industry on the tablelands for the with-research scenario, and 30% for the without-research scenario.

DAN158 was largely conducted under the auspices of the Weeds CRC. The total costs of *vulpia* research were determined as being $2.1 million which was the amount of DAN158 funding and the value of by NSW Agriculture's in-kind contributions to the Weeds CRC. An additional cost of $6.6 million was allowed for *vulpia* extension activities by NSW Agriculture over the 24-year period (1996 to 2020) of the benefit-cost analysis.

Economic, social and environmental effects

The results indicated high levels of economic benefits from the *vulpia* project. The annual net project benefit had a mean value of $58 million. The benefit-cost analysis generated a mean NPV of $196.9 million and a mean BCR of 22.2. These results demonstrate that research by NSW Agriculture into the improved management of *vulpia* has the potential to generate substantial long-term economic benefits. These benefits are equivalent to the value of the livestock production increases (in this case, wool) that result from reducing the *vulpia* and increasing the perennial grass content in a pasture. Other socio-economic aspects of the results showed that wool producers outside the New South Wales temperate areas lost economic surplus (from a mean -$21.7 million to -$47.8 million) because they were unable to adopt the cost-reducing technology and faced a reduced wool price. All wool consumers gained from *vulpia* research because of expanded wool production and lower wool prices. Improved *vulpia* management is also considered to produce important environmental benefits by encouraging a greater use of deep-rooted perennial grasses and the beneficial effects of these on mitigating soil problems and reducing water table discharges.

Funders and beneficiaries

The financial costs of DAN158 were met by the International Wool Secretariat with in-kind contributions from NSW Agriculture. The wool industry has been the principal beneficiary of the *vulpia* research and has appropriately provided about one third of the funding. All sections of the state's community will benefit in the long term from the environmental improvements that will result from increasing the perennial content of temperate pastures. These benefits are mainly expressed through reduced soil erosion and salinity and the reduced discharge of salts into waterways. However it would seem that the focus of this research has been on productivity gains and hence it seems appropriate the share of industry funding be half or more in the future implying that industry support of future extension programs is required.

Introduction

There has been a long history within the now former NSW Agriculture[1] of evaluating the returns from investment in specific research and development (R&D) projects. These evaluations were often used to support industry funding submissions and focused on the economic benefits from changes in farm productivity.

In 2003 NSW Agriculture began a more systematic process of evaluating the economic, social and environmental impacts of major programs of investment in research, extension and education. Five areas of investment were selected for evaluation of their economic, environmental and social impacts in 2003:

- an assessment of NSW Agriculture's wheat breeding program;
- an assessment of NSW Agriculture's advisory programs in water use efficiency;
- an assessment of net feed efficiency breeding research in beef cattle;
- an assessment of research and extension in conservation farming;
- an assessment of research and extension in annual weeds (*Vulpia*) in pastures.

This report presents the results of one of these initial evaluations conducted in 2003.

NSW Agriculture has been investing about $100m per year in research, extension and education activities making it the largest provider of research and development services within the NSW government sector. The opportunity cost of this investment is the benefit to the people of NSW were these resources used in other areas such as health and education. Hence it is important that NSW Agriculture can demonstrate that it uses these resources in ways that enhance the welfare of the people of NSW.

This suite of evaluations is designed to assess the economic, social and environmental impacts of some key areas of investment by NSW Agriculture. It is anticipated that each year another set of investment areas will be evaluated, so that a significant proportion of the Department's portfolio will be evaluated on a regular basis.

This evaluation process serves a number of purposes. The first is an external requirement for accountability in the way NSW Agriculture uses the scientific resources in its care. This evaluation process can also be used within NSW Agriculture to assist in allocating resources to areas likely to have high payoffs and to assist in designing research and extension projects that have clearly defined objectives consistent with the role of a public institution like NSW Agriculture. Working through this formal benefit cost framework gives those involved – economists, research and advisory officers and program managers - a greater appreciation of the paths by which, and the extent to which, research and extension activities are likely to have an impact at the farm level and hence lead to better projects. Part of this process is a greater understanding of other trends in the industry and of the extent to which "the market" is failing to deliver outcomes sought by the industry or by the community.

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[1] This work was done prior to the formation of the NSW Department of Primary Industries (on July 1, 2004) through an amalgamation of NSW Agriculture, NSW Fisheries, State Forests of NSW and the NSW Department of Mineral Resources.

We would like to be able to value all economic, environmental and social impacts and relate these to the investments made, but generally we are only successful in valuing some of these impacts because of:

- uncertainty about the technology on farm production both now and in the future;
- uncertainty about environmental and social impacts both now and in the future;
- uncertainty about the value of environmental and social resources both now and in the future;
- limited resources to undertake these evaluations.

Our approach has been to first describe qualitatively the economic, social and environmental impacts of the actual or proposed investment. We also describe the rationale for government investment from a market failure viewpoint which seeks to identify the characteristics of the investment resulting in farmers individually or collectively under-investing in the areas under consideration. We examine the share of public and private funding in the investment and compare this to a qualitative assessment of whether the benefits from the investment flow largely to farmers or largely to the community.

We then attempt to quantify as many impacts as practicable to arrive at the common measures of economic performance such as a benefit cost ratio. There are insights to be gained from persevering with an empirical benefit cost analysis even under uncertain scenarios. A key step is to identify not only the expected impact on an industry of the investment, the "with technology" scenario, but just as importantly, how the industry would continue to develop without the investment by NSW Agriculture, the "without technology" scenario. Rarely is the "without technology" scenario a no-change scenario because there are usually other sources of similar technologies leading to ongoing productivity growth. This quantitative approach also gives an indication of the relative importance of key parameters such as the rate and extent of adoption of technology, the on-farm impacts, and the size of the investment and its time path.

In assessing the "with" and "without" technology scenarios, key outputs from research and extension activities and communication strategies used are described to give credence to claims about the contribution of NSW Agriculture and to assumptions about the rate and extent of adoption of the technology.

In this study, we evaluate the economic benefits of research into the improved management of the major annual grass weed *vulpia* in the temperate pasture areas of south–eastern Australia.

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 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 pasture demands of livestock (Auld, Menz and Medd 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 $1.94 million annually, and totalled $13.64 million over the 7-year period 1995-96 to 2001-02 (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* spp. 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 Victorian is the focus of this evaluation.

Table 1. Summary of ABS data for the New South Wales and Victorian temperate pasture zones [a]

	Introduced pastures [b] ('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

[a] Australian Bureau of Statistics data for 1996-97; [b] introduced perennial grasses and legumes

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 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 this 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 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 former scenario usually implies a baseline that presumes an indefinite continuation of the research program, whereas the latter implies that none of the baseline research has been undertaken. For that reason, the with-research scenario seems to have limited relevance to many agricultural research programs since there has usually been some past research investment that helps to establish the baseline, eg. improved plant varieties usually incorporate improvements that resulted from earlier programs.

Other scenarios were proposed that embody different assumptions about the baseline. One of these scenarios is considered relevant to this weeds 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 this 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 that 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 content levels. 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 NSW 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 evaluated 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 adoption of these benefits over time by landholders, 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 due to technical change in the Australian wool industry.

A triangular probability distribution was chosen to represent the random variables of supply shift, adoption ceiling and lag in adoption. This continuous probability distribution is useful for situations when actual data is absent and parameter estimates need to be elicited, in this case from the *vulpia* researchers. 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, that 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^a			
- 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

[a] reduction in production cost (cents/kg) as a proportion of product price (cents/kg)

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. There could be a high level of correlation between the scenarios as it is possible that in the absence of the CRC input the 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 provide guidance on the extent of correlation, if any, between the benefits of the two research 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 model 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 through 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. A brief description of this model which is fully described in Jones, Dowling and Michalk (unpublished) is given as follows.

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

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

where π is net return ($ 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/head), *WPRICE* is the average price of wool ($/kg), *LSALE* is the number of culled livestock and *LPRICE* is the average price of culled livestock ($/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 ($/head), *RP* and *RC* are replacements and their costs ($/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 ($/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/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/hectare) of each species present in the pasture and the metabolisable energy of that species for a given day (MJ ME/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 *i*th 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:

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

where dW_i/dt is the daily growth of species *i* (kg/hectare), S_i is a species specific constant, GI_t is a daily growth index, W_t is the pasture biomass (kg/hectare), $WMAX_i$ is an asymptote for the biomass of species *i* (kg/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. 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 focussed 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 non-adopting 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 are given in Alston *et al*. (1995, p. 407):

$$\Delta CS_{TPZ} = P_0 CA_0 Z(1 + 0.5Z\eta_{TPZ}) \tag{8}$$

$$\Delta PS_{TPZ} = P_0 QA_0 (K - Z)(1 + 0.5Z\varepsilon_{TPZ}) \tag{9}$$

$$\Delta CS_{ROA} = P_0 CB_0 Z(1 + 0.5Z\eta_{ROA}) \tag{10}$$

$$\Delta PS_{ROA} = -P_0 QB_0 Z(1 + 0.5Z\varepsilon_{ROA}) \tag{11}$$

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 prices and quantities, *Z* is the relative price change, *K* is a 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 terms and were 0.3 and 1.4 for the TPZ and Australian wool supply, 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

TPZ = temperate pasture zone; ROA = rest of Australia

3.4 Benefit-cost analysis model

BCA 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. The stochastic analysis involved 5,000 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 percent. 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 project costs of $2.1 million spread over the first five years, and extension costs of $500,000 per annum for the first 5 years and $200,000 annually thereafter. 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:

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

4. Results

The summary statistics of the stochastic simulation modelling are given in Table 4 for the research independent case (i.e. $C = 0$) and in Table 5 for the case where the research scenarios are correlated (i.e. $C = 0.8$). The cumulative distribution functions (CDFs) for selected outputs of the modelling process are given in Figure 1.

The results presented 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 $107.7 million, while for the without-CRC scenario there was a $49.4 million increase in economic surplus. The net benefit from the CRC *vulpia* research was derived from the stochastic modelling process and, consequently, is not simply the arithmetic difference between the with-CRC and without-CRC values in Table 4. The net CRC research benefit result is represented by a probability distribution with a mean of $58.3 million, and maximum and minimum values of $187.4 and -$64.6 million respectively.

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 ($m)					
- with CRC	25.9	198.8	107.7	35.6	33.1
- without CRC	1.8	99.3	49.4	20.0	40.5
- net CRC benefit	-64.6	187.4	58.3	40.3	69.2
ΔPS ($m)					
- TPZ with CRC	37.4	282.6	153.8	51.0	33.1
- TPZ without CRC	2.9	140.4	70.4	28.5	40.5
- ROA with CRC	-88.2	-11.5	-47.8	15.9	33.3
- ROA without CRC	-43.4	-0.9	-21.7	8.8	40.6
ΔCS ($m)					
- with CRC	0.4	3.2	1.7	0.6	33.3
- without CRC	0.0	1.6	0.8	0.3	40.5
Benefit-cost analysis					
- NPV ($m)	-161.4	894.7	197.0	140.0	71.1
- BCR	-18.4	108.4	24.6	16.8	68.2

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

The benefits to producers from *vulpia* research are disaggregated into the two regions TPZ and ROA. Producers in TPZ gain from *vulpia* research, whereas producer surplus declines in ROA due to *vulpia* research. The effect of the with-CRC research is to increase the gains to TPZ (from mean $70.4 million to $153.8 million) and to increase the losses to ROA (from mean -$21.7 million to -$47.8 million). 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 *vulpia* research with a mean NPV of $197.0 million and a mean BCR of 24.6. However, there was substantial variability in the results of the benefit-cost analysis with the NPV ranging from a minimum of -$161.4 million to a maximum of $894.7 million with a coefficient of variation of 71.1.

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 upon 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 largely unaffected.

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 ($m)					
- with CRC	25.8	198.8	107.7	35.6	33.1
- without CRC	2.2	99.3	49.4	20.0	40.5
- net CRC benefit	-9.2	134.3	58.3	23.0	39.4
ΔPS ($m)					
- TPZ with CRC	37.5	282.2	153.8	51.0	33.1
- TPZ without CRC	2.6	140.7	70.4	28.5	40.5
- ROA with CRC	-88.1	-11.3	-47.8	15.9	33.3
- ROA without CRC	-43.4	-0.8	-21.7	8.8	40.6
ΔCS ($m)					
- with CRC	0.4	3.2	1.7	0.6	33.3
- without CRC	0.0	1.6	0.8	0.3	40.5
Benefit-cost analysis					
- NPV ($m)	11.6	765.3	197.9	107.8	54.5
- BCR	2.4	92.9	24.8	12.9	52.3

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

For the net CRC research benefit, although the mean remained identical at $58.3 million, the variability around the mean was substantially reduced. The range in values was from a minimum of -$9.2 million to a maximum of $134.3 million, and the coefficient of variation declined from 69.2 to 39.4. 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 CDFs for the economic surplus and benefit-cost analyses graphically illustrate these results (Figure 1). The NPV and BCR CDFs 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 CRC *vulpia* research. In the case of *C* =

0.8 there is a 90 per cent probability that the NPV would exceed $80 million and the BCR exceed 11.

For the two correlation cases the results given in Figure 1(c) and Figure 1(d) show that there is no difference in the CDFs 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 is an extremely low probability of a negative net CRC benefit. However, in the case of research independence there is around a 7 per cent probability that the net CRC benefit is less than zero.

The effect upon producer surplus change in the two regions for with-CRC and without-CRC *vulpia* research is presented in Figure 1(f). This illustrates how producers in the TPZ benefit from *vulpia* research whereas producers in ROA are worse of as a result of this research. The effect of the CRC is to magnify these gains and losses.

Social and Environmental Impacts

The economic benefits of vulpia research are shared by graziers, agribusiness and consumers in the form of increased income and have important social consequences for regional communities. An important social impact in this case is that because the technology only applies to the TPZ and because it is likely to result in a fall in wool price, woolgrowers outside the TPZ zone lose as a result of this technology. We estimate that their losses amounted to $21.7m without the project and $47.8m due to the project, ie. the project increases the losses to these producers from *vulpia* research by $26.1m. By simply summing these gains and losses to give a total gain to Australia of $58.3m per annum we are assuming that the community values the gains of temperate zone growers and the losses of those outside the temperate zone at the same rate but if the community were to weight the losses to those outside the temperate zone more highly then aggregate benefits are not as large, and may even become negative.

There are a number of on-site and off-site environment impacts associated with the *vulpia* management technology that have not been valued in this study. Increasing the proportion of the landscape under perennial species will reduce deep drainage to the watertable. An on-site benefit from reduced deep drainage that has not been quantified is a lowering of the incidence of dryland salinity across a catchment. A reduction in deep drainage also results in off-site benefits from minimising salt loads entering streams and rivers which can have negative downstream impacts upon environmental assets and urban infrastructure. Water quality in rivers and streams is improved as a result of increased perenniality as nitrates, phosphates and sediment levels in runoff from paddocks are higher with annual plant species. Such improvements in water quality can lead to off-site environmental benefits. However, if there is any significant reduction of dilution flows in rivers and streams as a consequence of increased perenniality then salinity concentrations may increase in rivers with negative environmental consequences.

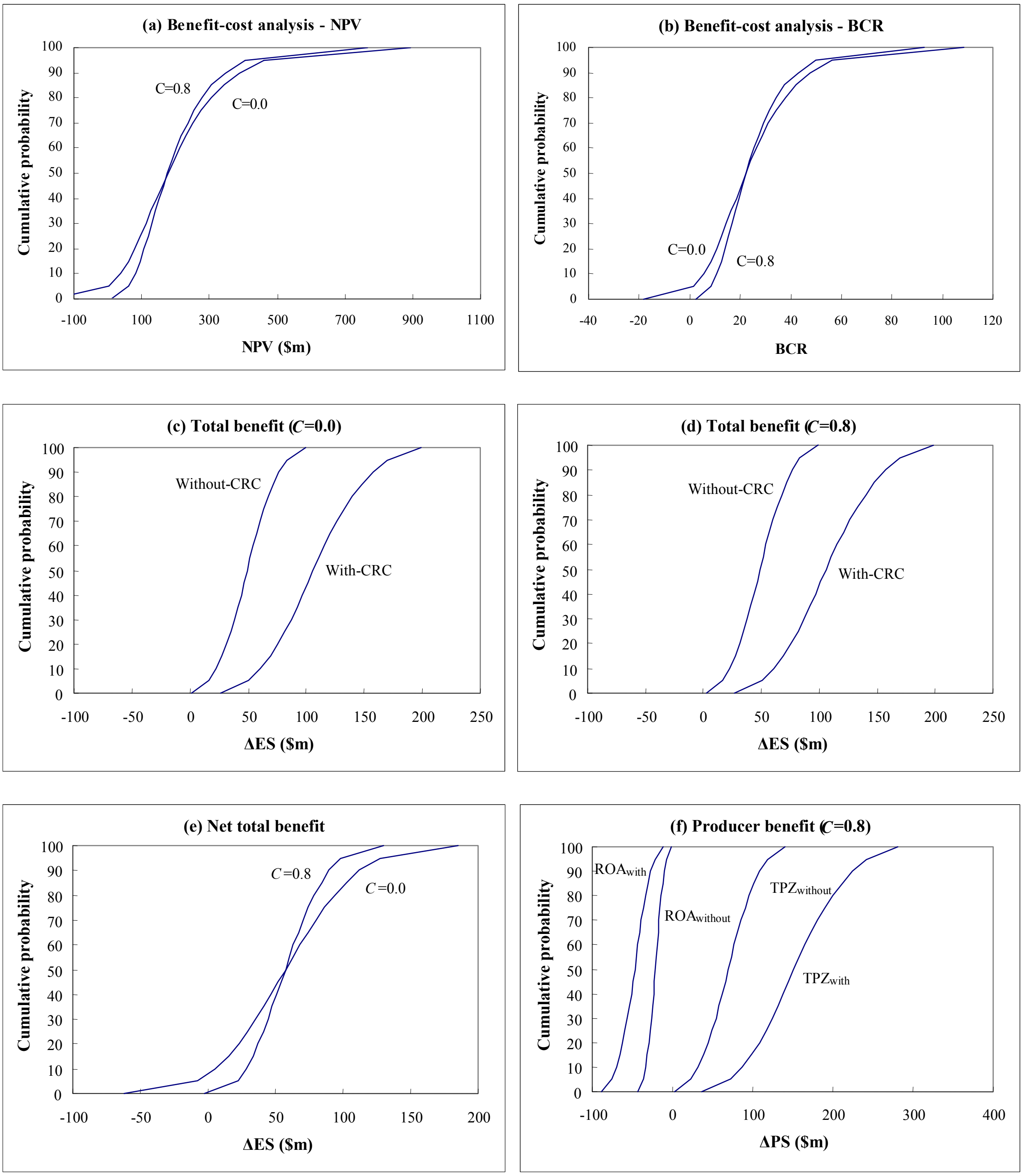

Figure 1. Cumulative distribution functions for the net present value (NPV), benefit-cost ratio (BCR), economic surplus change (ΔES) and producers' surplus change (ΔPS) of *vulpia* research (*C* = rank-order correlation coefficient; TPZ = temperate pasture zone; ROA = rest of Australia)

5. Discussion

This paper presents estimates of the economic costs of the pasture weed *vulpia* and the long-term benefits of improved *vulpia* management. *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. 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 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, such as phalaris and cocksfoot 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 from 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. In this study, the use of different values for the supply shift indicates the uncertainty that surrounds the research outcomes from which benefits are estimated. 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, eg. 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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