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Agricultural Economics 30 (2004) 143–155

AGRICULTURAL ECONOMICS

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The economic benefits of rabbit control in Australian temperate pastures by the introduction of rabbit haemorrhagic disease

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Received 8 February 2002; received in revised form 25 July 2002; accepted 30 October 2002

Abstract

The European rabbit is present in most Australian environments and causes economic loss in agricultural systems by reducing production and imposing control costs on producers and governments. Research into rabbit control has recognised the need for reliable benefit–cost analysis to justify inputs into rabbit management. This paper provides estimates of the costs of rabbits in Australian temperate pasture systems and of the long-term benefits of reducing rabbits by the introduction of rabbit haemorrhagic disease (RHD). Rabbits impose annual costs on wool producers in the temperate pasture areas of between 7.1 and 38.7 million Australian dollars (mA$) depending on their density. Controlling rabbits by RHD has the potential to generate substantial long-term economic benefits by reducing grazing competition with sheep. Reducing rabbit costs by 25% generated 15-year net present values (NPVs) between 18.4 and 97.3 mA$ at various pre-RHD rabbit densities. A 50% reduction in rabbit costs increased the total NPVs between 36.9 and 202.4 mA$, virtually all of which was captured by temperate area wool producers. The corresponding benefit–cost ratios were between 2.9:1 and 16.2:1 for a 25% rabbit reduction and 5.9:1 and 32.4:1 for a 50% reduction, where the total costs of the RHD program in the temperate pasture areas were incurred by the wool industry. The analysis provides guidelines for the economic evaluation of other pest problems in agricultural production systems.

Keywords: Rabbits; Economic modelling; RHD; Australia

1. Introduction

The European rabbit (*Oryctolagus cuniculus*) is considered to be Australia's most damaging vertebrate pest (Williams et al., 1995). The rabbit arrived in Australia with European settlement and its subsequent spread has been documented at the most rapid rate of any colonising mammal (Caughley, 1977). Rabbits are present in most Australian environments from sub-alpine to deserts but are absent from northern Australia and central western Queensland. Fifteen years ago, the area of Australia inhabited by rabbits was estimated to be about 4 million km^2, which was mainly south of the Tropic of Capricorn and included most of Australia's agricultural land (Croft, 1987). There have been no recent estimates of this habitat range and it is likely to have remained unchanged, although rabbit densities in some areas have been reduced substantially by the introduction of rabbit haemorrhagic disease (RHD) in 1995 (Neave, 1999). The rabbit's noxious status throughout Australia emphasises its unequivocal importance as an agricultural and environmental pest.

Rabbits cause economic loss in agricultural systems by reducing production, imposing control costs on producers, governments and communities, and by

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0169-5150/$ – see front matter
doi:10.1016/j.agecon.2002.10.002

degrading natural resources. In livestock production systems, rabbits deplete and degrade pastures, reduce livestock production and support other pest animals which prey on livestock. Until recently, the economic aspects of the rabbit problem in Australia have not been well quantified although the need for such information is recognised. Allen et al. (1998) state that Australian research on vertebrate pests has failed to provide an adequate framework for benefit–cost analysis that was any more complex than a simple comparison of the differences between doing nothing and achieving a level of control. In relation to rabbits, realistic benefit–cost analyses have not been attempted despite the large amounts of resources that have been devoted to rabbit management (Parer and Pech, 1988). This view is reinforced by the observation that the absence of rigorous benefit–cost analysis has limited the quality and objectivity of the advice on rabbit problems available to producers. The activities of rabbit management agencies are also constrained by this lack of information (Choquenot et al., 1998). Williams et al. (1995) consider that much of the existing information on the economic costs of rabbits in Australia is anecdotal or derived from localised experiments and that this makes it difficult to reliably quantify the economic effects of rabbits in other than localised areas. Such information problems are not unique to rabbits and relate to Australian vertebrate pest research in general (Tisdell, 1982).

In relation to agricultural weeds, Vere and Auld (1982) observe that economic evaluations assist in establishing the relative importance of weeds as pests, in rationalising control programs and in directing weeds research. Each of these issues is relevant to the rabbit problem in Australia. Williams et al. (1995) state that it is necessary to clearly define the economic problem caused by rabbits, to evaluate the benefits and costs of control options, and to understand why the collective actions of producers have not resulted in a socially optimal level of control. Such observations indicate that there are private and social dimensions to the rabbit problem which need to be economically evaluated to justify investment in rabbit control. The development of private and public strategies to reduce rabbit damage should ideally be based on reliable estimates of rabbit costs and the economic returns to implementing control practices.

This paper presents estimates of the economic costs of rabbits and the potential long-term benefits of achieving levels of rabbit control in Australian temperate pasture systems from the introduction of RHD. The focus is on the rabbit problem in perennial pasture systems which occur in the high rainfall regions (>600 mm per annum) of southeastern Australia. The bulk of this region extends from northern New South Wales to western Victoria and contains most of Australia's introduced temperate pastures. Rabbits have historically been abundant throughout these areas (Wilson et al., 1992). Official census statistics and pasture surveys indicate that these temperate pasture areas cover about 16.7 and 10.1 million ha in New South Wales and Victoria, respectively (Pearson et al., 1997). These areas also support 50 and 90% of each state's sheep and cattle populations (Australian Bureau of Statistics, 2000). The analysis is necessarily ex ante since the full biological impact of RHD on rabbit populations in this region has yet to be assessed.

2. The costs of rabbits to the Australian livestock industries

2.1. Previous cost estimates

Parer and Pech (1988) identify the private costs of rabbits to be reduced production, control operations and government levies, and the public costs to be environmental damage, rabbit research and development and the external costs caused by rabbit spread. Private and public benefits result from reductions in these costs. A selection of the rabbit cost and control benefit estimates that have been derived on a state or regional basis in Australia is presented in Table 1. These estimates relate to impacts of rabbits on agriculture and not to the environment as the latter do not appear to have been economically evaluated (Manson, 1998). Also excluded are smaller area studies that refer to the economic costs or control benefits of rabbits but which cannot be realistically extrapolated over larger areas. Many of these impact studies are cited in Williams et al. (1995) and most are based on subjective or anecdotal rather than quantitative information (Saunders and Kay, 1999).

Reid (1953) values the increased wool and meat production from the introduction of the myxomatosis

Table 1
Some broad area rabbit impact estimates in Australian agriculture

Reference	Area	Impact description
ACIL (1996)	Australia	Increased production from an 80% reduction in rabbits from RHD valued at 600 mA$ annually, comprising 300 mA$ wool, 150 mA$ beef cattle, 80 A$/m crops and 70 mA$ sheep meat
Croft (1987)	New South Wales	Value of increased wool production from rabbit control in the central slopes areas estimated at 65 A$/ha
Flavell (1988)	Australia	Annual value of increased agricultural production by controlling rabbits with myxomatosis estimated at 70 mA$
Henzell (1989)	South Australia	Rabbits cause annual losses of livestock production worth 20 m$ in the pastoral zone and annual crop losses of 6.5 m$
Manson (1998)	Australia	Estimate of annual benefits where RHD reduces wool production costs by 1% in three regions (pastoral, wheat-sheep and high rainfall); in all zones, wool producers gain 27 mA$ and consumers gain 11 mA$; with variable cost reductions between regions, wool producers gain 177 mA$ and consumers gain 51 mA$; foreign wool producers lose 28 mA$ because of reduced world wool prices
Reid (1953)	Australia	Increased sheep and wool production from myxomatosis valued at £ 34 m in 1952–1952; converted to 590 mA$ in 1990 values by Williams et al. (1995)
Sloane et al. (1988)	Australia	Annual cost of reduced sheep productivity from rabbit grazing valued at 89.8 mA$ based on 1985–86 values; annual control costs in wool industry are 5 mA$
Waithman (1979)	New South Wales	Rabbit control under myxomatosis increases shorn sheep numbers by 21%, wool production by 26% and sheep and lamb slaughterings by 25 and 12%
Williams et al. (1995)	Australia	Annual value of sheep production foregone due to rabbits is 115 mA$

virus to be £A34 million in 1953. The main component of this estimate is an additional 32 kt of wool which is valued at £A24 million on the assumption that wool prices would not fall with increased supply. The equivalent value of this estimate 42 years later is 590 mA$ (Williams et al., 1995). Sloane et al. (1988) find that after kangaroos, rabbits are the major vertebrate pest causing economic loss to Australian woolgrowers. Costs are assessed in terms of the reduced sheep production due to rabbit grazing competition and are estimated at 90 mA$ annually. Rabbits are responsible for 8% of the total wool industry losses (1.2 billion Australian Dollars (bA$)) from weeds, pests and pasture diseases combined. This estimate is based on a very small sample of woolgrowers. It also assumes a constant gross margin over all woolgrowing regions, although the sheep productivity loss parameters assessed by the respondents vary between 30% in semi-arid areas and 5% in more favourable regions. The annual value of sheep production foregone from rabbit damage in the arid pastoral zone of South Australia is estimated to be 17 mA$ on the assumption that sheep production would increase by 40% under rabbit control (Henzell, 1989).

ACIL's (1996) estimate of annual benefits of 600 mA$ from the release of the RHD is equal to 3% of the annual gross value product of the Australian rural sector in 1993. This estimate is based on rabbit distribution data from Wilson et al. (1992) in which all local government areas (LGAs) are rated according to seven rabbit density classifications ranging from absent to abundant. The benefits of an assumed 80% reduction in rabbit numbers are evaluated by relating the density parameters to each LGAs gross value of production in 1993 at an assumed production increase level. For example, the potential increase in sheep production in high rabbit density areas is assumed to be between 30 and 40%, while cattle production increases between 20 and 30%. Applying these parameters over all LGAs, the estimated increases in livestock numbers are 15 million sheep and one million cattle over 10 years.

A common feature of the Sloane et al. (1988) and ACIL (1996) estimates is that fixed values for production and prices are used to calculate the aggregate losses and benefits and so prices do not react as production levels change due to rabbits or rabbit control. Also, the benefits of rabbit control accrue only to producers. Where the rabbit problem is large, such as under the production increases proposed by ACIL (1996), production and price levels will be affected, particularly under the competitive structures of Australia's livestock commodity markets. Tisdell (1982) recognises the likelihood that where a pest animal sufficiently affected production, additional costs would fall on consumers because of higher prices for the pest-affected commodities. In either the with or without rabbit situations, the net economic effects of changes in commodity prices and consumer demand need to be established. Evaluations which do not consider these effects will not be a true reflection of rabbit costs nor the benefits of rabbit control.

One study which does not suffer from this shortcoming is by Manson (1998), who estimates the benefits to the Australian wool industry from the release of RHD using an equilibrium displacement model of the Australian apparel wool sector to determine the potential benefits of rabbit reductions from RHD. Rather than evaluating an actual decline in rabbit numbers from RHD, the effects of a percentage reduction in the cost of wool production attributable to the disease are simulated. Two area scenarios are considered assuming a 1% fall in wool production costs; the pastoral zone where rabbits are considered to have had their greatest impacts, and all regions that would benefit from RHD (pastoral, wheat-sheep and high rainfall). A third scenario is also considered in which the regional effects of RHD were varied under cost reductions of 25, 5 and 2.5% for the pastoral, wheat-sheep and high rainfall zones, after Sloane et al. (1988).

Under the first scenario, pastoral zone woolgrowers gain 4.1 mA$ annually but those in the other two zones lose 0.6 mA$ from the spill-over effects of a lower world wool price. Foreign wool consumers gain almost 1.4 mA$ per annum. When all zones are considered, the gain to all woolgrowers increases to 22.5 mA$ annually while wool consumers more than double their gain to 11.2 mA$, giving a total benefit of 33.7 mA$. The greatest benefits are realised under the third scenario, which is also considered the most realistic. The total annual benefit is nearly 227.3 mA$, of which Australian woolgrowers derive 176.6 mA$ with the remainder being captured by foreign wool consumers. Foreign wool producers lose 28.3 mA$ annually because of reduced world wool prices. This result reflects Australia's dominance of the world wool market and it also indicates that it would not be in the interests of woolgrowers in other countries to have rabbits controlled in Australia, even at a level that only resulted in a 1% reduction in wool production costs. Sensitivity analyses are conducted on the supply and demand elasticities used in these estimates to examine the changes in the distribution of benefits between woolgrowers and wool consumers. The key feature of Manson's study is that it quantifies the impacts of rabbits in terms of price and quantity effects in the markets for the affected commodity. It thus improves on earlier estimates which assume that production changes do not affect commodity prices.

2.2. Rabbit control

Landholders are responsible for controlling rabbits under various state laws. Many control methods are adopted including poisoning, shooting, fumigation, trapping and shelter destruction. Two major events in the biological control of rabbits in Australia were the successful introductions of the myxomatosis virus in the early 1950s and RHD in 1995. The former initially caused substantial reductions in rabbit numbers which were greatest in the areas where virus-carrying mosquitoes are seasonally abundant. Although the efficacy of this disease has declined since its introduction, it remains a major factor in limiting rabbit numbers (Williams et al., 1995).

RHD is a disease caused by a calicivirus specific to the European rabbit that causes death within 30–40 hours of infection (Williams et al., 1995). RHD was being tested as a potential biological control agent for rabbits in Australian when it escaped from offshore quarantine in late 1995 and rapidly established itself throughout mainland Australia. Three years later, RHD was estimated to occur in at least 70% of the rabbit's range and has since had a variable impact. RHD has been most effective in the drier regions where rabbit populations in some areas initially fell up to 90% and have since remained at 15–20% of pre-RHD densities (Neave, 1999). The impact of RHD in temperate areas has been much more variable and some populations have been largely unaffected (Saunders et al., 1999).

The full impact of RHD on Australia's rabbit problem will not be evident for years, although its potential impact on the agricultural sector appears to be favourable (Saunders and Kay, 1999). Australia has a small rabbit industry that could be adversely affected by RHD, but domestic rabbits can be vaccinated against the disease. RHD is also likely to adversely affect the industry based on the harvesting of wild rabbits. These impacts remain to be determined in the long term but they are anticipated to be small relative to the benefits to the broader pastoral industries (Neave, 1999). Similarly, there is no evidence of RHD affecting non-target native and other fauna.

The analysis that follows is based on the reality of RHD successfully achieving permanent reductions in the effects of rabbit grazing competition in temperate pasture systems. In the first instance, the annual costs of rabbits are estimated as the value of livestock production foregone from rabbit grazing. The second utilises these opportunity cost estimates to determine the net benefits of reducing rabbits from RHD over time.

3. Methods

The economic modelling system used to evaluate the benefits of controlling rabbits in temperate pastures is illustrated in Fig. 1. The evaluation sequence is to determine the changes in livestock production at the farm level, to simulate these changes within a livestock industry model, and to calculate the resulting economic welfare changes and the relative benefits and costs of improved rabbit control over time. This system comprises a linear programming (LP) model of a temperate pasture system which maximises the returns per hectare from various types of sheep and wool production, a structural econometric model (SEM) of the Australian grazing industries, a regionally-disaggregated economic surplus model and a benefit–cost model. The system enables the impacts of rabbits to be evaluated in terms of the costs they impose on livestock producers and the livestock industries. Returns to improved rabbit control are evaluated on the proposition that the benefits of controlling rabbits are equivalent to the production losses prevented. Applying this system to the rabbit problem overcomes the benefit–cost information deficiencies identified by Allen et al. (1998) and Choquenot et al. (1998). It enables the true economic impact of rabbits to be determined rather than the financial costs based

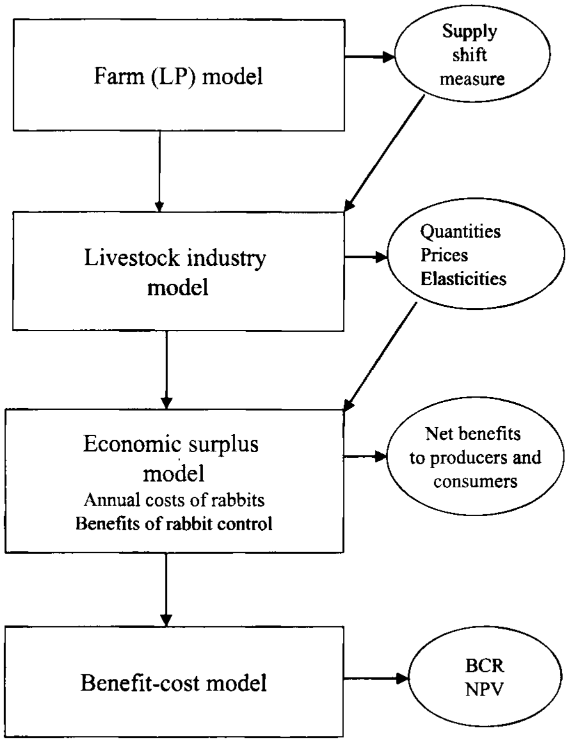

Fig. 1. Economic modelling system for evaluating rabbit impacts in pastures.

on constant prices that have been estimated in most previous studies. The distinction is that an economic evaluation concerns the social welfare effects of rabbits and their control. These effects are measured by changes in economic surplus that incorporate both the quantity and price changes caused by the pest. Measuring welfare changes requires knowledge of the supply and demand functions for the relevant commodities and how supply functions shift because of the pest and its management. This system is applicable in this ex ante assessment of the potential economic returns to the release of RHD, as well as in an ex post context once the impact of the program on rabbit populations has been assessed.

The base pasture in the LP model is a mixture of introduced perennial grasses (40%), legumes (20%) and weeds (40%) which is a typical temperate pasture composition in southeastern Australia (Dellow et al., 2002). Dry matter production increases with the introduced species content and decreases as weeds increase. Monthly dry matter production from each pasture is measured as megajoules of metabolisable energy (MJ ME per hectare) which is matched with the feed energy demands of the sheep activities (MJ ME per head) to determine the production levels which maximise the gross margin per hectare for each activity. The sheep production activity selected is the production of 21 μ wool from a self-replacing Merino breeding flock, which is the dominant form of livestock production in the southeastern temperate pasture areas.

A major effect of rabbits in a pasture system is to reduce dry matter availability to livestock. To measure this effect in the LP model, rabbits are specified as a competing livestock activity. Grazing competition between sheep and rabbits is usually measured in terms of dry sheep equivalents (DSEs) but there is little information on the relationship between rabbit density and impact on pastures. The generally accepted measure of the relative food intake of sheep and rabbits is that 16 rabbits per hectare are equivalent to one DSE, falling to 12 rabbits per DSE in the higher rainfall areas with the estimate of 10–12 most often quoted (Myers et al., 1994). Grazing competition from rabbits is higher in low rainfall areas where pasture growth is limited and the proportion of available pasture eaten by rabbits is larger. Rabbits compete with livestock when pasture biomass is below 250 kg of dry matter per annum which relates to many arid area pastures in Australia (Williams et al., 1995). Some temperate pastures produce a much larger annual biomass (up to 15,000 kg/ha) and measuring rabbit impacts in these situations is problematic because it cannot be assumed that their feed would have been eaten by livestock. One experiment on New South Wales central tablelands pastures found that the stocking foregone from rabbit grazing equalled between 0.32 and 1.06 DSEs/ha, depending on the extent of compensatory pasture growth (Choquenot et al., 1998).

There is little information on the ME requirements of wild rabbits. Domestic rabbits require 0.8 MJ ME per day (Scholaut, 1982) which is about 24 MJ ME per month, and this is the rabbit pasture demand specified in the LP model. Density is the other major determinant of rabbit impacts in a pasture system. Again, this factor is difficult to estimate because rabbit numbers are highly variable within and between years in response to factors such as season, feed availability, reproduction, disease and predation. Following the suggestion of Williams et al. (1995) that a medium density (under normal non-plague conditions) is 1–4, 2–10 rabbits/ha are simulated to represent low, medium and high densities. These densities are compared to a base density approaching zero. Some rabbits are usually present in any temperate pasture but actual numbers vary from negligible to plague proportions at any particular time. At the base density, rabbits are considered to have no measurable feed demands.

The feed requirement and density estimates enable rabbits to be specified as a livestock activity that competed with sheep for the limited pasture resource but generated no economic return. This procedure provides estimates of the proportional supply shift parameter (K) which is a critical variable in the subsequent economic surplus modelling. K is calculated in each instance as the production cost difference as a proportion of the price per kilogram for 21 μm wool. These estimates correspond to the supply shift that results when the production process and the input–output mixes are allowed to adjust (via the LP model) to accommodate a new technology (Alston et al., 1995).

The SEM grazing industries model provides the necessary link to the LP model because many producers are affected by rabbits and the scale of the problem is sufficiently large to change commodity quantities and prices. The SEM contains a total of 94 endogenous variables and was dynamically simulated from 104 quarterly observations over the period 1971 and 1996 (Vere et al., 2000). Simulating the impacts of rabbits on grazing involves a shock simulation in which the level of an appropriate exogenous (explanatory) variable is altered to simulate changes in the endogenous variables of interest such as production and prices, re-solving the model and comparing the results with those of the base model solution. Differences in the simulated values of the endogenous variables are held to be attributable to rabbits since the influences of the other explanatory variables are already incorporated in the model's estimates. The exogenous variable adjusted for the simulation is the area of introduced pastures which is a significant determinant in seven of the 15 equations that represent livestock breeding decisions and production. Rabbit impacts are simulated with a 5% adjustment to this variable to generate the national equilibrium wool quantity and price, as well as the long-term Australian wool supply elasticity for use in the economic surplus modelling (Table 2).

Table 2
Wool parameter values and annual rabbit cost estimates

	Unit	Source	Rabbit density per hectare					
			0	2	4	6	8	10
Production (kt)								
TPR	182.0	Australian Bureau of Statistics (2000)						
ROA	580.0	Vere et al. (2000)						
ROW	1908.0	ABARE (1999)						
Consumption (kt)								
Australia	18.3	Vere et al. (2000)						
ROW	2651.7	ABARE (1999)						
Elasticities								
TPR supply	0.35	Kokic et al. (1993)						
ROA supply	1.4	Vere et al. (2000)						
ROW supply	1.0	Assumed						
Australian demand	−0.8	Hill et al. (1996)						
ROW demand	−1.5	Hill et al. (1996)						
Wool price/kg	750	Vere et al. (2000)						
Production costs (Cents/kg)			424.7	428.6	432.5	436.7	441.4	446.1
Cost differences (Cents/kg)				3.9	7.8	12.0	16.7	21.4
Supply shifts (%)				0.52	1.04	1.60	2.23	2.85
Annual rabbit costs ($m)[a]				7.04	14.09	21.69	30.27	38.73

Regions are temperate pasture region, rest of Australia, rest of the world.
[a] Costs to wool producers in the temperate pasture region; calculation made using the DREAM© model (Alston et al., 1995; IFPRI, 2001).

Economic surplus methods are commonly used to evaluate the social welfare effects of production constraints such as rabbits or of the adoption of production-increasing technology such as rabbit control. Three important propositions regarding economic surplus as a welfare measure are that a commodity's demand price is its unit value to consumers, its supply price is its unit value to producers, and that welfare changes are additive irrespective of to whom they accrue (Harberger, 1971). Accepting these propositions enables welfare changes to be measured in terms of economic surplus where the area under the demand curve measures the benefit to consumers and the area under the supply curve measures the benefit to producers.

The economic surplus model can take various forms to represent different technology and market scenarios. Most models incorporate a parallel supply shift to determine total welfare changes which are distributed between producers and consumers according to the values of the supply and demand elasticities. An extension of the standard, closed economy, non-traded commodity model is to disaggregate the level of the evaluation into different geographic regions (Davis, 1994; Fig. 2). The rationale for this disaggregation is that the implication of the standard model that all producers face the same production costs because they are equally affected by pests is inconsistent with the resource and climatic variations that exist between regions. The cost structures of producers are similarly variable but prices are equal across regions. Moreover, price changes from pest activity in one region will have spill-over effects in other regions. In a competitive industry such as the Australian wool industry, pests will reduce production and increase prices. Further considerations are whether the affected commodities are traded and the country's export share of international markets (Edwards and Freebairn, 1982). Regional differences in the economic impacts of rabbits have been verified in Australia (Manson, 1998), and Australia is the world's major wool exporter. A disaggregated economic surplus model is therefore used to evaluate

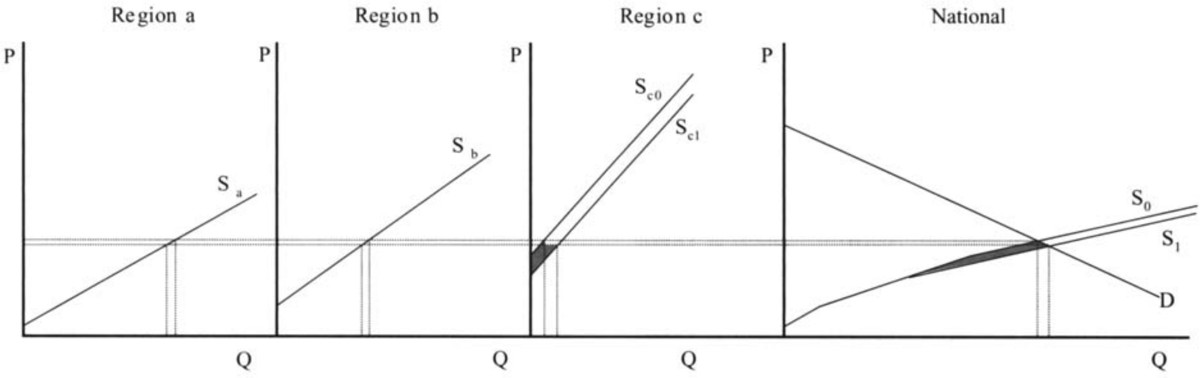

Fig. 2. Regional disaggregation of supply shift from technology adoption (after Davis, 1994).

the costs of rabbits and the benefits of improved rabbit control in Australian temperate pastures.

Alston et al. (1995) specify several disaggregated economic surplus models of the welfare effects of production changes in a region which is a sufficiently large part of an industry to influence prices in other regions and countries. The models relate to technology adoption that increases production but they can also be used to measure the welfare costs of constrained production. One model captures the price spill-overs from the adoption of a technology that is only relevant in one region. Adoption benefits that region's producers by reducing their production costs, producers elsewhere cannot adopt the technology and lose from reduced commodity prices, while consumers in all regions gain from the lower prices. This model is relevant to many agricultural technologies in Australia because the target problems are regionally specific or environmental constraints prevent adoption in other regions. The formulae for a two-region model with price spill-overs are:

$$\Delta CS_1 = P_0 C_{1_0} Z(1 + 0.5Z\eta_1) \quad (1)$$

$$\Delta PS_1 = P_0 Q_{1_0}(K - Z)(1 + 0.5Z\varepsilon_1) \quad (2)$$

$$\Delta TS_1 = \Delta CS_1 + \Delta PS_1 \quad (3)$$

$$\Delta CS_2 = P_0 C_{2_0} Z(1 + 0.5Z\eta_2) \quad (4)$$

$$\Delta PS_2 = -P_0 Q_{2_0} Z(1 + 0.5Z\varepsilon_2) \quad (5)$$

$$\Delta TS_2 = \Delta CS_2 + \Delta PS_2 \quad (6)$$

ΔCS, ΔPS and ΔTS represents consumer, producer and total economic surplus changes in regions 1 and 2, P_0 and Q_0 are the equilibrium prices and quantities in each region, ε and η are the price elasticities of supply and demand, K is the proportional supply shift parameter and the relative price change Z is defined as $-(P_1 - P_0)/P_0$. The annual costs of livestock production foregone because of rabbits are calculated with Eq. (2) with a sign change to represent an inward shift of the wool supply function. The costs fall on wool producers in the temperate pasture areas. It is recognised that wool producers in other areas also suffer costs from rabbits but the LP model which determines the K values only relates to temperate pasture systems. In estimating the benefits of controlling rabbits, the three regions considered are the temperate pasture region (TPR), the rest of Australia (ROA) and the rest of the world (ROW). All elasticity and wool production and consumption values and sources are given in Table 2. No regional wool consumption was assumed because it is historically very small. Elasticities are medium to longer-term to represent the effects of RHD in wool producers' supply responses over time. The average farm wool price used in the LP and the economic surplus modelling is 7.50 A\$/kg.

Benefit–cost analysis completes the methods of this evaluation. Benefits are estimated for 25 and 50% reductions in the five rabbit densities from the LP model to represent the effects of RHD. At the lowest density (2 ha^{-1}), RHD reduces rabbits to 0.5 and 1 ha^{-1} (2.5 and 5 ha^{-1} at the highest pre-RHD density of 10 rabbits/ha). The initial costs of research associated with the release of RHD along with the costs of program monitoring and evaluation are also considered. Initial laboratory testing

(1991–1993) by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) was valued at 750,000 A$ (CSIRO, 1997). In addition, approximately 600,000 A$ was spent by the National RHD Proponent Group between 1994 and 1996 (N. Newland, personal communication, 2001), and between 1996 and 2000, 8.1 mA$ was spent by state and federal agencies and two rural industry funding bodies as part of the National RHD Program (M. Bomford, personal communication, 2001). The Victorian government allocated 10 mA$ to the Rabbit Buster Program with the objective of integrating RHD with traditional rabbit control methods. As there are no zone-specific cost estimates for the promotion of RHD, one-third of the total expenditures of all governments on this program (6.5 mA$) is attributed to rabbit control in the temperate region. These cost estimates are incorporated in the benefit–cost analysis in which all values were projected over 15 years and discounted at 5%.

4. Results and discussion

The results in Table 2 demonstrate the large annual costs that rabbits impose on wool producers in Australia's temperate pasture areas. At the lowest density of 2 ha^{-1}, the annual value of wool production foregone from grazing competition by rabbits is 7.04 mA$. This increases to 32.38 mA$ at the highest density of 10 rabbits/ha. The marginal cost changes between the two lowest densities are larger than the changes at the high densities, and so the values of the supply shift parameters (K) decrease between the incremental densities. The unit production cost difference (from zero rabbits) at a density of 4 ha^{-1} are double the cost difference at a density of 2, whereas the relative cost differences at a density of 10 rabbits is only 28% greater than the unit cost at an eight rabbit density. This suggests that there is a saturation density at which additional rabbits have a very small effect on wool production costs relative to the low densities. Further simulations with the LP model indicate that the marginal increases in unit production costs were negligible at rabbit densities of 20–25 ha^{-1}. The annual costs of rabbits at the higher densities are therefore relatively constant.

Controlling rabbits in temperate pastures by the introduction and persistence of RHD has the potential to generate substantial long-term economic benefits. By reducing grazing competition with sheep in the TPR, the main effect of RHD is to increase wool production and this reduces wool prices in the three regions. This benefits TPR producers and all consumers, while producers in the ROA and ROW lose from the reduced wool prices. The shares of these welfare changes are distributed between wool producers according to the price elasticities of wool supply and demand. Producers typically benefit most from an inelastic supply and an elastic demand, and the converse applies to consumers.

If RHD was successful in retrieving 25% of the annual costs of rabbits across the five densities, the 15-year NPVs of the total benefits would lie between 18.4 and 97.3 mA$ (Table 3). A 50% reduction in rabbit costs increases total NPVs to between 36.9 and 202.4 mA$. Virtually all of the benefits accrue to TPR wool producers because the regional wool supply is price inelastic relative to the elastic demand for wool at the Australian and international levels. Losses to ROA wool producers are small in comparison, but the losses to ROW producers were approximately three times larger. Australian wool consumers derive negligible benefits from RHD because of the low level of domestic wool consumption (only 2% of national production). The net welfare effect on the international wool market is positive under both rabbit reduction levels because the benefits to foreign consumers outweigh foreign producer losses in every instance. These results are consistent with the theory of modelling the economic effects a production-increasing technology such as RHD that affects a particular region which forms a significant part of a national industry which in turn is large internationally.

A critical factor on which the validity of these results depends is rabbit density in a pasture system. As previously indicated, rabbit numbers in pastures are highly variable over time but there is little consistent evidence on temperate pastures to guide the selection of appropriate densities for economic analysis. Recent research on the New South Wales central tablelands suggests that densities in rabbit-prone areas peak in summer at between 6 and 7 ha^{-1} and that a density pressure of 4 ha^{-1} would be normal throughout the year (Choquenot et al., 1998). The results for densities beyond 6 rabbits/ha are therefore at the upper end of the potential benefit scale. Nevertheless, the benefits

Table 3
Benefits of reducing rabbits with RHD in wool production from Australian temperate pastures: mA$ (15-year NPVs at 5%)[a]

	Rabbit density per hectare				
	2	4	6	8	10
25% reduction					
Producers surplus' change					
TPR	18.25	36.52	56.18	78.32	100.12
ROA	−0.55	−1.10	−1.69	−2.37	−3.02
ROW	−1.82	−3.63	−5.56	−7.78	−9.95
Consumers surplus' change					
TPR[b]	0	0	0	0	0
ROA	0.02	0.03	0.05	0.07	0.09
ROW	2.52	5.05	7.76	10.82	13.83
Total economic surplus change					
TPR	18.25	36.52	56.18	78.32	100.12
ROA	−0.53	−1.07	−1.64	−2.30	−2.93
ROW	0.71	1.42	2.20	3.03	3.88
50% reduction					
Producers surplus' change					
TPR[b]	36.51	73.05	112.44	159.79	200.49
ROA	−1.10	−2.21	−3.39	−4.73	−6.05
ROW	−3.63	−7.26	−11.17	−15.57	−19.90
Consumers surplus' change					
TPR	0	0	0	0	0
ROA	0.03	0.07	0.11	0.15	0.19
ROW	5.05	10.09	15.53	21.64	27.66
Total economic surplus change					
TPR	36.51	73.05	112.44	156.73	200.49
ROA	−1.07	−2.14	−3.28	−4.58	−5.86
ROW	1.42	2.83	4.36	6.07	7.76
Benefit–cost criteria[c]					
25% reduction NPV	18.42	36.85	56.71	79.06	97.27
25% reduction BCR	2.94	5.89	8.98	12.65	16.17
50% reduction NPV	36.85	73.74	113.50	158.28	202.39
50% reduction BCR	5.89	11.79	18.16	25.32	32.38

Regions are temperate pasture region, rest of Australia, rest of the world.
[a] Calculation made using the DREAM© model (Alston et al., 1995; IFPRI, 2001).
[b] No wool consumption is assumed in the TPR.
[c] Discounted over 15 years at 5%; temperate pasture region.

of RHD control of rabbits remains substantial at the lower densities. A further economic consideration is the assumed effectiveness of the RHD. The results are based on effectiveness levels of 25–50% which may be conservative since the overall efficacy of the RHD program has yet to be assessed. While greater levels of rabbit population reduction were achieved in some temperate areas as RHD first spread (Saunders et al., 1999; Neave, 1999), we consider the modelled densities to be realistic in the long term.

Comparisons with Manson's (1998) results are not straightforward because of the different methods and assumptions used. Manson estimated the annual benefits of the RHD program across the three main Australian agricultural zones (pastoral, wheat-sheep and high rainfall) and also for other parts of the world. The two main differences are that Manson assumes uniform (1%) production cost reductions (supply shift parameters) across the three zones and sensitises them for higher cost reductions, whereas the current study uses a formal production systems model to directly calculate the supply shifts. Because the LP model relates only to temperate pasture systems, valid comparisons can only be made with Manson's high rainfall zone results. The second difference is that Manson estimates annual benefits from RHD whereas the current study estimates annual costs and projected benefits over 15 years assuming that rabbit control benefits from RHD are equivalent to the production losses prevented. If the value of production loss estimates can be considered in the same context as Manson's annual benefits for the high rainfall zone, the loss estimates of the present study are more than fourfold the benefit estimate of 9.4 mA$ at the supply shift estimate that is comparable to Manson's 1% cost reduction (at a rabbit density of 4 ha^{-1}). The NPV estimates also differ from the earlier study as they are projected over time and consider different levels of RHD effectiveness. The largest NPV (202.4 mA$) results where RHD permanently halves the impact of rabbits at the highest density. This estimate is comparable to Manson's total benefits of 227.3 mA$ under the assumption of variable cost reductions between the three regions.

The main implication of the results of this analysis is that rabbits at any level impose significant annual costs on temperate pastures which, at low densities in particular, may not be recognised by livestock producers. The benefit–cost estimates support the desirability of introducing and maintaining RHD in Australia's temperate pastures. The benefit–cost ratios based on the total benefit estimates are between 2.9:1 and 16.2:1 for a 25% rabbit reduction, and 5.9:1 and 32.4:1 for a 50% reduction, where the total costs of the RHD program were apportioned to wool production. These ratios indicate that even at low levels of effectiveness and low rabbit densities, RHD yields positive economic benefits over time. Whether RHD is capable of permanently controlling rabbits to minimal impact levels remains to be established, particularly in the temperate areas where it has been observed to be less effective than under drier conditions. The main potential for RHD appears to be as an initial reduction agent which should be complemented by conventional biological control methods. However, research has yet to establish this potential.

The benefit–cost procedure assumes that the wool industry is the only beneficiary of RHD, and that all the costs of the current program which has been sponsored by various Australian government and rural industry organisations are discounted against wool industry benefits. Governments have now ceased funding the program although industry is continuing to support research on RHD. Costs incurred by producers are now minimal as they are mostly relying on the natural spread of RHD to maintain its effectiveness. Other pasture-based grazing activities such as beef cattle and prime lamb production are similarly affected by rabbits and controlling rabbits will therefore benefit those industries also. Where the benefits of the RHD program can be attributed to industries other than wool, it is appropriate to offset a share of the program costs against these benefits. Also, the RHD program has resulted in a significant reduction in the costs incurred by producers in controlling rabbits. For example, savings in the costs of rabbit poisoning programs since the introduction of RHD in central western NSW are estimated to be 1.24 mA$ per annum (Saunders et al., 2002).

It is recognised that in restricting this analysis to Australia's southeastern temperate areas, the benefits from RHD to wool producers in other regions are ignored. This is because the structure of the economic surplus model used implies that Australian wool producers outside the temperate areas lose economic surplus because they are unable to benefit from the cost-reducing RHD technology. As indicated above, RHD occurs in other climatic zones and has been equally and potentially more effective in controlling rabbits there than in the temperate areas. However, the determination of the benefits to producers in other zones is not possible because of the non-availability of production system models for these zones. Could such additional benefit calculations be made, the overall benefits of RHD to Australia would likely be considerably greater than those presented in this paper.

The value of this economic approach is that it recognises that the presence and the control of pests in agricultural production systems can have important effects on the markets for the affected commodities. In the case of rabbits in Australian temperate pastures, it improves on previous economic evaluations (with the exception of Manson, 1998) that have not considered the quantity and price changes caused by pests. The main value of the estimates is in assisting improved decisions concerning the allocation of R&D resources into the rabbit problem in Australia. As such, this study provides guidelines for undertaking economic evaluations of other agricultural pests problems in Australia and elsewhere. Reliable data, particularly in relation to program costs, is an essential requirement of this evaluation process.

Acknowledgements

We thank Mary Bomford (Bureau of Rural Sciences) and Nicholas Newland (formerly of the RHD Proponent Committee) for providing the cost estimates for the RHD program, and Debbie Templeton of the Australian Centre for International Agricultural Research for supplying the DREAM© model and providing guidance in its use.

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