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THE ECONOMIC BENEFITS OF THE BIOLOGICAL CONTROL OF RABBITS IN AUSTRALIA, 1950–2011

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Wild European rabbits are serious agricultural and environmental pests in Australia; myxoma virus and rabbit haemorrhagic disease virus have been used as biocontrol agents to reduce impacts. We review the literature on changes in rabbit numbers together with associated reports on the economic benefits from controlling rabbits on agricultural production. By using loss–expenditure frontier models in with and without biocontrol scenarios, it is conservatively estimated that biological control of rabbits produced a benefit of A$70 billion (2011 A$ terms) for agricultural industries over the last 60 years. The consequences for ongoing rabbit control and research investment are discussed.

JEL categories: N57, Q16, Q27, Q57

Keywords: Australia, biological control, economic benefit, livestock industry, rabbit

INTRODUCTION

Introduced European rabbits, *Oryctolagus cuniculus*, are Australia's most costly vertebrate pest. They not only cause widespread losses to pastoral and agricultural production but also have severe environmental impacts.[1] The economic and environmental costs of rabbits would be far more severe if not for the successful release of two biological control agents over the last 60 years: myxoma virus that was introduced in 1950 and rabbit haemorrhagic disease virus, which became established in 1995.[2] Myxomatosis initially caused heavy mortality of rabbits, but

1 McLeod, *Counting the cost*; Gong, Sinden, Braysher, and Jones, *The economic impacts*; Cooke, Rabbits.
2 Fenner and Fantini, *Biological control of vertebrate pests*.

changes in rabbit resistance enabled partial recovery of rabbit numbers. Similar resistance is developing against rabbit haemorrhagic disease (RHD) with associated slow resurgence of rabbits.[3]

This study reviews the economic benefits to Australian agriculture, mainly the meat and wool industries, from using myxomatosis and RHD. In particular, we consider the major benefits reported after myxomatosis first spread, the likely increases in the costs of control as rabbits developed resistance to myxomatosis and then the benefits regained as a high level of rabbit control was reimposed through the use of RHD.

In making assessments of this kind, it cannot be simply assumed that, in the absence of these biological controls, Australia would still have a serious rabbit problem. After all, when attempts to introduce myxomatosis in New Zealand failed, other solutions were found.[4] Presumably, Australia would most likely have followed a similar path to New Zealand if myxomatosis had not been introduced. On that basis, a 'with' and 'without' myxomatosis methodology is preferable to a 'before and after' methodology when considering likely economic benefits. It is also important to acknowledge that, apart from the actions of the biological control agents, other factors influenced the final outcomes. Government agencies, farmers, and other land managers also make decisions in deciding whether or not to augment disease impact by applying further control methods such as poisoning, warren destruction, or fumigation. Accordingly, we have used the concept of a loss–expenditure frontier to allow for an economic trade-off between production losses and expenditure on rabbit control.[5] This partial analysis approach enables comparison of the marginal changes in losses and expenditure to estimate the benefits from releasing biocontrol agents.

By using published information to help construct loss–expenditure frontiers, we have been able to reach a preliminary estimate of the magnitude of benefits resulting from the release of myxomatosis and RHD as well as a framework for evaluating the likely economic outcomes and limitations of introducing additional biological control agents for rabbits. In recent years, considerable investment has been made in exploring biological control options for a range of vertebrate pests.[6] Understanding of the potential economic benefits and the social constraints that might limit those actions has previously been neglected even though it is just as important as the understanding of ecological processes or the behaviour of a particular biological control agent.

3 Nyström *et al.*, Histo-blood group antigens; Elsworth, Kovaliski, and Cooke, Rabbit haemorrhagic disease; Sandell, Promoting woodland; Saunders, Kay, Mutze, and Choquenot, Observations.

4 Filmer, Disappointing tests; Gibb and Williams, The rabbit in New Zealand.

5 McInerny, The simple analytics of natural resource economics; Gong, Sinden, Braysher, and Jones, *The economic impacts*, p. 10.

6 Henzell, Cooke, and Mutze, The future biological control of pest populations; Saunders, Cooke, McColl, and Peacock, Modern approaches.

METHODS

Production losses and rabbits

There are many publications that report the economic costs of rabbits in Australia.[7] Some are of particular importance because they provide information associated with the introduction of myxomatosis and subsequently RHD.[8] Not all use the same methods of assessment, whereas others only consider a specific industry such as wool and sheep meat. This necessitates care when making comparisons or drawing conclusions. Likewise, there are many references from New Zealand that are useful for considering how rabbit control in Australia might have played out in the absence of myxomatosis.[9] Other papers are valuable for considering landholder decisions that set limits to rabbit control at a national level.[10]

We took care to validate conclusions from published papers and, where possible, we expanded on previous information, as the following example shows. Reid estimated the economic benefits from releasing myxomatosis based on increases in wool and sheep meat production.[11] There was an immediate, substantial increase in greasy wool production of 70 million lbs (32 m kg), or 5.5 per cent of total Australian production worth £24 million at the time, and Reid considered that another £10 million could be added for extra sheep slaughtered and added to flocks. This seems justifiable because in 1952/53 and 1953/54, sheep slaughtering value made up 36 per cent and 42 per cent of that of wool.[12] Increased wool and sheep meat production, totalling £34 million, was equivalent to A$1,057 million in 2011 terms.

Waithman similarly analysed wool and livestock production within NSW, comparing Australian Bureau of Agriculture and Resource Economics (ABARE) data for the 5-year periods before and after myxomatosis spread.[13] He showed that greasy wool production rose by 26 per cent and the number of sheep shorn increased by 21 per cent. The number of sheep and lambs slaughtered increased by 25 per cent and 21 per cent, respectively. Moreover, wool cut per head only increased by 4 per cent and lambing rates by only 1 per cent so the main factor was clearly the greater carrying capacity of the largely rabbit-free pastures. Other studies from individual farms confirmed that removal of rabbits allowed

7 Fennessy, The impact of wildlife species; Waithman, Rabbit control in New South Wales; Sloane and King Pty Ltd, *The economic impact of pasture weeds*; Manson, Identification of public and private benefits; Saunders, Kay, Mutze, Choquenot, Observations; McLeod, *Counting the cost;* Vere, Jones, and Saunders, The economic benefits of rabbit control; Gong, Sinden, Braysher, and Jones, *The economic impacts*.

8 Reid, Some economic results of myxomatosis; ACIL Economics and Policy, *The economic importance of wild rabbits*.

9 Gibb and Williams, The rabbit in New Zealand; Lough, *The current state of rabbit management*; Nugent *et al.*, Why 0.02%? A review.

10 Aspinall, Effects of rabbits; Ferraro and Burnside, *West 2000: A Case Study*.

11 Reid, Some economic results of myxomatosis.

12 Australian Bureau of Agriculture and Resource Economics, *Commodity statistics*.

13 Waithman, Rabbit control in New South Wales.

significant increases in flock size but relatively smaller increases in wool cut per head.[14] Sheep numbers across Australia increased from 109 million in 1951/52 to almost 165 million by 1965/66 and sheep numbers subsequently peaked in 1970/71. However, much of this later increase in sheep production could be attributed to improved, sown pasture and super-phosphate application.[15]

Unfortunately, Reid did not analyse gains in beef cattle production. Nonetheless, to confirm that the productivity of the beef industry closely paralleled changes in sheep and wool production, we again used data from Waithman showing that beef cattle numbers in NSW increased by 10 per cent in the immediate aftermath of myxomatosis and the number of cattle slaughtered increased by 26 per cent. To calculate the additional monetary benefits to beef production from myxomatosis, we assumed that:

1. decreases in rabbit numbers brought similar benefits to both sheep and cattle production;
2. Australian beef cattle and sheep numbers in 1953 were 10.45 million and 115.97 million, respectively[16]; and
3. beef cattle are equivalent to 10 dry sheep (i.e. 1 cow = 10 dry sheep equivalents or DSEs),[17] but we used a factor of eight to accommodate flock and herd structures (i.e. the expected mix of lactating ewes or cows, dry sheep, and cows, etc.).

We concluded that, if the benefit to sheep was £34 million, benefits to cattle production would be $34 \times 8 \times 10.45/115.97 = £24.5$ million. This meant that the total losses to sheep and cattle production prior to myxomatosis would therefore have been £58.5 million annually, which is equivalent to A$1866 million today.

As myxomatosis generally lowered rabbit numbers by 90 per cent, it can be argued that, prior to its introduction, production forgone by the livestock industries due to rabbits would have been equivalent to about A$2073 million annually (2011 dollars).[18] After myxomatosis, this would have been reduced to about A$200 million annually for a decade or more.

Similar attention was paid to the management decisions made by landholders involved with rabbit control. Myers described the situation immediately before and after the spread of myxomatosis.[19] He stated that, prior to myxomatosis, almost every farmer carried out rabbit control but usually with techniques that facilitated harvesting of carcasses and skins. When rabbits were low, little effort was made to reduce numbers further. Only a few farmers ripped warrens instead of poisoning. New poisons such as 1080 were slow to be taken up because they did

14 Fennessy, The impact of wildlife species.
15 Waithman, Rabbit control in New South Wales.
16 Australian Bureau of Agriculture and Resource Economics, *Commodity statistics*.
17 Anon, Agriculture notes.
18 Myers, A survey of myxomatosis.
19 Myers, A survey of myxomatosis.

not facilitate harvesting of skins. Myers considered that killing large numbers of rabbits when they were abundant was not conducive to control. It helped rather than hindered the rabbit population and was a palliative for the agricultural industries rather than a solution to the problem. Nonetheless, after myxomatosis spread, expenditure and effort put into rabbit control changed markedly. The number of farmers practicing rabbit control fell from over 90 per cent to between 10 and 40 per cent depending on the agricultural region. The expenditure on a few properties surveyed fell from £1,500–2,000 a year to only £100–300 (about 10 per cent of former costs).

After RHD became established, Ferraro and Burnside likewise found that in low rainfall areas of western New South Wales, few landholders carried out work aimed at eliminating rabbits even though such work appears to be beneficial.[20] Only one-third of the 75 landholders involved in a programme called 'West 2000' wished to continue rabbit control without external support. The majority would not undertake any additional work without subsidies and a small group was simply disinterested, irrespective of incentives. As a community, land-managers set a level of participation based on their resources and clearly made a judgement as to where an economic balance lies between losses to rabbits and expenditure on control. Similar conclusions can be reached from statements by Aspinall in considering landholder decisions on rabbit management in the dry Central Otago region of New Zealand.[21]

Expenditure on rabbit control

To consider present-day expenditure on rabbit control, we used data collated by Gong *et al.*[22] They calculated that national management, administration, and research expenditure on control of all vertebrate pests amounted to A$122.7 million annually in 2008/09 and that rabbit control amounted to 16 per cent of that expenditure, i.e. close to A$20 million annually.[23] This figure agrees with a previous independent estimate of Bomford and Hart.[24] However, it is known that in New South Wales and South Australia, the expenditure on rabbit poisoning was reduced by about 70 per cent when RHD was introduced.[25] Furthermore, assuming that other rabbit control measures such as warren ripping were proportionally reduced, national expenditure on rabbit control just prior to the release of RHD in 1995 may have been as high as A$60–70 million annually.

Current expenditure of about A$20 million can also be broadly substantiated from chemical use for rabbit control. An average of 220 kg of raw 1080 poison

20 Ferraro and Burnside, *West 2000: A Case Study*; McPhee and Butler, Long-term impact of coordinated warren ripping; Cooke, Jones, and Gong, An economic decision.
21 Aspinall, Effects of rabbits.
22 Gong, Sinden, Braysher, and Jones, *The economic impacts*.
23 Gong, Sinden, Braysher, and Jones, *The economic impacts*, Table 4.4.
24 Bomford and Hart, Non-indigenous vertebrates in Australia.
25 Saunders, Kay, Mutze, and Choquenot, Observations.

powder has been used in Australia annually since RHD was introduced, and 87 per cent of this, 190 kg, is used for rabbit control[26]; implying that about A$9 million (2011 A$) is spent on 1080 poisoning alone based on costs for laying poison baits.[27] To this may be added the use of other poisons (pindone) and at times expenditure is similar for warren destruction, especially in drier areas. Contract costs for warren ripping are at least A$10 per warren, and the scale of such work is apparent from the example of the South West Rabbit Control Group in NSW, which ripped 290,000 rabbit warrens using powerful bulldozers.[28] That particular project was implemented to remove remaining rabbits after RHD spread, but as the results are long-lasting, it is best seen as a high initial investment that was recouped over a longer period (15 years or more).[29] Expenditure on fumigation and other forms of rabbit control is relatively low because the high labour component in treating individual rabbit warrens means that it is not so commonly undertaken.

Finally, it can be argued from economic principles that if the losses caused by rabbits across Australia are estimated to be in the order of hundreds of millions of dollars, then expenditure to counter the problem should bear a close relationship to likely losses, especially those that land managers see as avoidable.[30] As rabbits began to recover from myxomatosis and losses to rabbits increased, expenditure on control rose proportionally to maintain or optimise landholder financial returns.[31] The converse was also true. Expenditure on rabbit poisoning in south-eastern Australia dropped by approximately 75 per cent when RHD became established.[32]

Loss–expenditure frontiers

Using the information considered above, we established a series of approximate loss–expenditure frontier curves.[33] These provided scenarios for Australia '*with myxomatosis*' when (i) the disease was first released then (ii) 45 years later when rabbits had gained considerable resistance to the disease.[34] A third curve, providing a '*without myxomatosis*' scenario, was also derived to picture how things might have been had the myxoma virus not been introduced.

26 Australian Pesticides and Veterinary Medicines Authority, *Review findings*; G. Saunders unpublished records).
27 Saunders, Kay, Mutze, and Choquenot, Observations.
28 Ferraro and Burnside, *West 2000: A Case Study*; McPhee and Butler, Long-term impact of coordinated warren ripping; Connellan and Croft, Ripping tales.
29 McPhee and Butler, Long-term impact of coordinated warren ripping.
30 McInerney, The economic analysis of livestock disease.
31 Myers, A survey of myxomatosis.
32 Saunders, Kay, Mutze, and Choquenot, Observations.
33 McInerny, The simple analytics of natural resource economics; McInerny, Old economics for new problems; Gong, Sinden, Braysher, and Jones, *The economic impacts*.
34 Fenner and Fantini, *Biological control of vertebrate pests*.

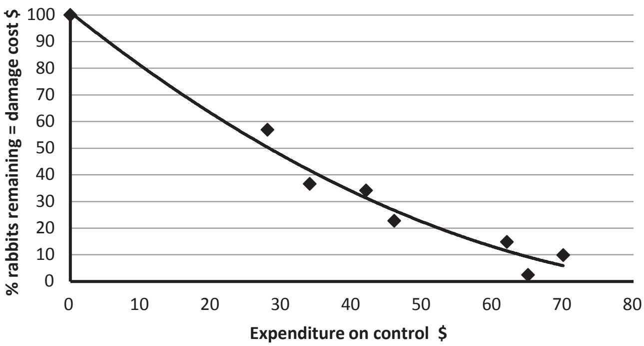

Figure 1. Experimental results showing how the relative abundance of rabbits and presumed economic losses are reduced with increasing expenditure on rabbits control (from Cooke, Rabbit control).

In addition to the economic data available, we expected that the series of 'loss–expenditure frontier' curves should bear a consistent, progressive relationship with one another. In determining the likely shape of these curves, we initially considered information on the costs and efficacy of rabbit control.[35] That work made it clear that rabbit abundance and associated losses should decline as expenditure increases, irrespective of the methods or combinations of methods used. Nonetheless, such simple relationships do not necessarily apply where landholders make a choice to optimise returns. Losses to rabbits are reduced quite quickly with increasing expenditure but then decline more slowly because costs increase when mopping up the last rabbits (Figure 1). However, because many land-managers do not sustain vigorous control efforts as the need for rabbit control reduces, the shapes of the loss–expenditure frontiers are influenced as much by management decisions as technical capacity to reduce rabbit numbers.

To establish the 'loss–expenditure frontier' curves, the first baseline curve was set up assuming that there is an annual unavoidable loss to rabbits of about A$200 million (2011 dollars) across Australia. Experience showed that after myxomatosis became widely established, it was hard to encourage further rabbit control by landholders, and a similar situation was met immediately after RHD spread. Combined information from Reid, Waithman, and Myers indicate that losses to rabbits remained at about A$200 million after myxomatosis spread and Bomford and Hart and Gong *et al.* also estimated losses due to rabbits at A$200–207 million in the aftermath of RHD.[36]

For the second curve, we assumed that as rabbits developed increasing resistance to myxomatosis, the shape and position of the loss–expenditure frontier

35 Cooke, Rabbit control.

36 Reid, Some economic results; Myers, A survey of myxomatosis; Waithman, Rabbit control in New South Wales; Bomford and Hart, Non-indigenous vertebrates in Australia; Gong, Sinden, Braysher and Jones, *The economic impacts*.

changed. Fortunately, ACIL Economics and Policy estimated potential losses to rabbits in the mid-1990s, when rabbits reached their highest levels since the introduction of myxomatosis.[37] From these estimates, we accepted a potential loss without additional rabbit control of approximately A$600 million annually but assumed that landholders would balance expenses and losses to maximise returns. In effect, landholders would have tackled only the 'avoidable' costs (i.e. those above A$200 million) with national expenditure approaching A$60–70 million annually. The shape of this curve is set so that costs (loss + expenditure) are minimised at an expenditure of about A$70 million annually (see above).

The third loss–expenditure curve provided a scenario of the situation had myxomatosis not been introduced. This curve was anchored using (i) data from Reid, Myers, and Waithman showing that the value of livestock production forgone by landholders enmeshed with the rabbit harvesting industry had been approximately A$2000 million in 2011 dollar terms, and (ii) the reasonable assumption that direct chemical or mechanical methods of rabbit control would have been unlikely to reduce rabbits below the levels achieved by myxomatosis.[38] However, in the absence of any national estimates of rabbit control expenditure before myxomatosis was introduced, and despite poisoning being widely used and great effort being put into rabbit drives and trapping, the loss–expenditure frontier is difficult to place precisely.[39] In effect, following the observations of Myers, we have assumed that wool and meat growers spent very little on effective rabbit control compared with the size of the problem but instead relied on the rabbit industry as a palliative to partially meet that need or offset costs.

The shape of the third curve also incorporates New Zealand's experiences in dealing with rabbits in the absence of myxomatosis. When attempts to introduce myxomatosis into that country failed, major advances in rabbit control were mainly achieved through highly organised poisoning and shooting campaigns. Nevertheless, expenditure in this scenario is high. New Zealand is a small country in comparison with Australia but uses about 500 kg 1080 powder for rabbit baits each year compared with less than 200 kg in the whole of Australia.[40] This applies even though the 1080 concentration on rabbit baits is similar in both countries.[41] In parts of the McKenzie Basin, for example, annual expenditure on rabbit control had reached NZ $10–12 per livestock unit (one sheep with lamb) before the arrival of RHD, which then brought about a 75 per cent reduction in rabbit abundance and a reduction in annual rabbit control expenditure to about NZ $2–4 per livestock unit.[42] Lough also reported on estimates made by the Rabbit Calicivirus Disease Applicant Group that national expenditure on rabbit control

37 ACIL Economics and Policy, *The economic importance of wild rabbits*.
38 Reid, Some economic results; Myers, A survey of myxomatosis; Waithman, Rabbit control in New South Wales.
39 Rolls, *They all ran wild*.
40 Lough, *The current state of rabbit management*.
41 Nugent *et al.*, Why 0.02%?
42 Lough, *The current state of rabbit management*.

was NZ $22 million and that national losses might be as high as NZ $50 million. This is a fivefold difference in ratios compared with Australia's estimated losses of A$200 million with an annual expenditure on rabbit control calculated at A$20 million.[43]

Another manifestation of higher costs in New Zealand is that the limits to control without government subsidy are reached in Central Otago, where annual average rainfall is about 385 mm and carrying capacity averages about one sheep per hectare.[44] By contrast, in Australia, this limit is closer to 200–250 mm annual average rainfall and a carrying capacity of 0.2 sheep per hectare.[45] With this in mind, the third curve was iteratively set to reflect the fact that expenditure for the 'without myxomatosis' scenario could be up to five times higher than for the 'with myxomatosis' scenario to achieve an equivalent high level of rabbit control.

RESULTS

Trends in rabbit numbers and economic losses

Figure 2 summarises information available on changes in rabbit numbers in the arid pastoral area of north-eastern South Australia associated with the introduction of myxomatosis and then RHD in an area where poisoning and warren ripping were seldom applied.[46] In that region, where mosquitoes are scarce, the release of European rabbit fleas *Spilopsyllus cuniculus* in 1969 also enhanced the spread of myxomatosis, although results of this kind were localised and did not necessarily have a major economic consequence nationally.[47] The figure clearly shows the recovery in rabbit abundance as myxomatosis progressively became less effective, followed by the re-establishment of a high level of control through the release of RHD.

Some of the published economic losses attributed to rabbits are also indicated in Figure 2, and it is notable that, since the early estimates, all subsequently reported losses are relatively low but broadly consistent.[48] This is interpreted as indicating that, although rabbits gained disease resistance and showed greater potential for increase, significant counter-measures were taken in agricultural areas to keep rabbits down. The rise of rabbits in arid pastoral areas where control measures were unaffordable would have had relatively small economic impact on a national scale because those areas do not contribute as heavily to agricultural production as higher rainfall zones.

43 Gong, Sinden, Braysher, and Jones, *The economic impacts*.
44 Aspinall, Effects of rabbits.
45 Ferraro and Burnside, *West 2000: a case study*.
46 Saunders, Cooke, McColl, and Peacock, Modern approaches.
47 Cooke, Changes in the age-structure and size.
48 Reid, Some economic results; Waithman, Rabbit control in New South Wales.

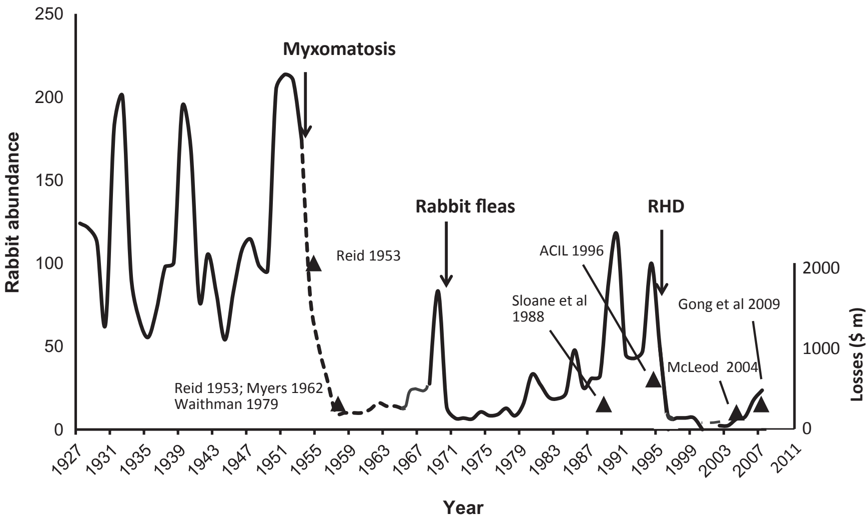

Figure 2. Diagram showing how rabbit abundance in semi-arid South Australia has varied through time in response to the release of biological control agents. The estimated Australia-wide economic losses to rabbits (black triangles) are also shown. Scale for losses shown on right-hand side of figure. Figure adapted from Saunders *et al.*, Observations.

Loss–expenditure frontiers: validation and implications

The series of loss–expenditure frontier curves we developed are presented in Figure 3. In this model, they have the form:

$$y = 200 \quad (1)$$

$$y = 200 + 400e^{-0.042X} \quad (2)$$

$$y = 200 + 1800e^{-0.015X} \quad (3)$$

where y = production loss to rabbits and x = expenditure on rabbit control.[49] The first equation represents the ‘unavoidable’ loss to rabbits, where landholders do not see the rabbits as a problem worth expenditure. Equation 2 approximates the situation where rabbits have developed partial resistance to biological control, and some expenditure on rabbit becomes necessary to avoid increasing losses. Equation 3 is the assumed ‘without myxomatosis’ scenario.

49 All valued in 2011 dollars.

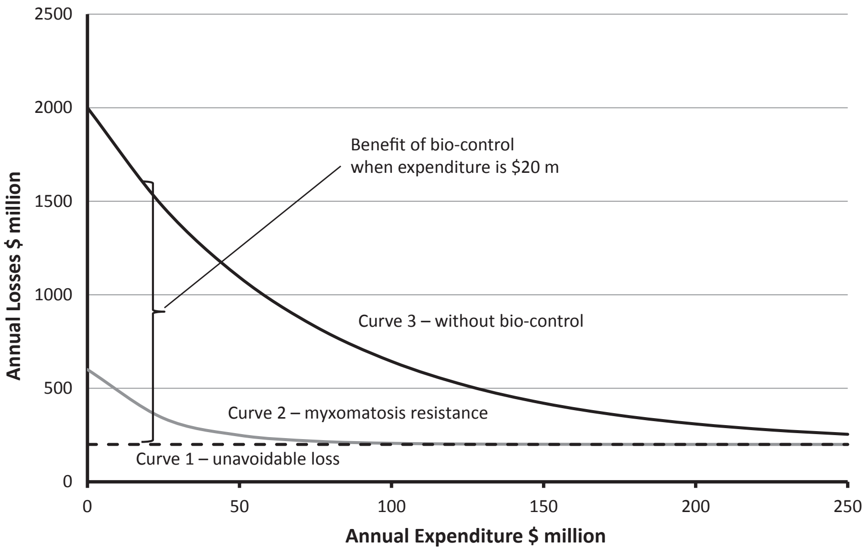

Figure 3. Series of loss–expenditure frontier curves constructed using available data from the literature: Curve 1 (dotted) – immediately after the release of myxomatosis (and RHD) when landholders undertook little additional rabbit control work; Curve 2 (grey) – the situation 45 years after release of myxomatosis with increasing resistance to myxomatosis in rabbits, just before the release of RHD; Curve 3 (black) – the 'without myxomatosis' scenario.

Because much of the available information has been used in establishing the model, its validation and improvement is only possible using previously unused information or new information that may come to hand (e.g. better information on pre-myxomatosis expenditure). For instance, we can refer to the published data from Sloane, Cook and King Pty Ltd, who considered that the production losses caused by rabbits to Australia's wool industry were then A$94.5 million per annum despite expenditure of A$4.5 million on rabbit control.[50] Those authors further considered that the loss to wool growers was about two-thirds of the total economic loss to agriculture because the main rabbit populations were located in the Australian temperate pastoral zone. The broad-scale losses were therefore about A$180 million and control costs about A$9 million (2011 dollars). This point is located close to the *y*-axis on curve one but, although supportive of the general model, does not provide a particularly robust test. Generally, the published estimates of losses to rabbits and expenditure for their control lie close to curves one and two and indicate that the actions of myxomatosis and RHD together with additional rabbit control expenditure by farmers have contained economic losses caused by rabbits within a small range.

50 Sloane, Cook and King Pty Ltd, *The economic impact of pasture weeds*.

The introduction of new technologies, in this case myxomatosis and RHD and better tools for rabbit control, shifted the loss expenditure frontier.[51] Consequently, the benefit of research is shown by the difference between the 'without biocontrol' and the 'with biocontrol' curves at a given expenditure. From Figure 3, it can be seen that, if expenditure averaged about A$20 million annually, the meat and wool industries should have benefited by about A$1400 million annually from the introduction of myxomatosis. When expenditure is low, it should further be noted, the benefit estimated under the 'with-' and 'without myxomatosis' methodology is only a little more conservative than a 'before and after' methodology.

While only broad conclusions can be drawn from this general model, it is nonetheless useful to try to derive a figure for the cumulative benefits of introducing biocontrol agents to focus attention on the magnitude of benefits that resulted. If we consider expenditure on rabbit control in the 45 years from 1950 until the introduction of RHD in 1995, it clearly varied from being very low, perhaps A$10million, immediately after myxomatosis but gradually increased to about A$70 million in the early 1990s (all in 2011 dollars) as rabbits increased. The accumulated marginal benefits over this period suggest that the introduction of myxomatosis would have produced a net benefit of about A$54 billion (2011 dollars) despite its eventual decline in effectiveness. The introduction of RHD effectively re-set conditions to something close to the immediate post-myxomatosis situation, providing an added benefit of perhaps A$350 million annually through the immediate reduction of avoidable losses (A$300 million) and reduction of expenditure (A$45 million). This figure is compatible with other published information in that Manson considered that RHD would have benefited the wool industry alone by some A$177 million by reducing production losses. The sheep meat and beef industries presumably benefited as well.[52]

Of course, it is arguable that these overly precise benefits of introducing biocontrol agents may change substantially if the presumed loss–expenditure frontier curves we have generated prove to be poor approximations to the real situation (if the 'without-myxomatosis' curve showed a steeper decline with expenditure for example). However, as this curve is anchored at A$2000 million (the pre-myxomatosis livestock production foregone because of rabbits) and national expenditure on rabbit control remains relatively low, our estimates of benefits should be relatively insensitive to changes in the slope of the loss–expenditure curve in either direction. It certainly would not change the broad conclusion that the introduction of myxomatosis and RHD has been worth many billions of dollars to the major agricultural industries. By keeping rabbits low, the benefits of biological control to Australia's livestock and farming industries over the last 60 years were probably in the order of A$54,000 million from myxomatosis alone

51 Gong, Sinden, Braysher, and Jones, *The economic impacts*, p. 39.
52 Manson, Identification of public and private benefits.

plus A$16,000 million from myxomatosis and RHD together approaching a total of A$70 billion (2011 dollars).

CONCLUSION

While the series of loss–expenditure frontier curves presented in Figure 3 is derived from a mix of quantitative and qualitative information, it nonetheless provides a basic conceptual framework for considering the benefits of Australia's war on rabbits. The curves provide insights into the benefits and consequences of the introduction of myxomatosis and a more robust alternative to a simplistic scenario in which it is assumed that losses to rabbits would have remained much as they were had not myxomatosis or RHD been introduced.

Nonetheless, it is recognised that curve three (Figure 3) is very much a first approximation of the loss–expenditure frontier in the absence of myxomatosis. As already pointed out, it was assumed that prior to the introduction of the disease, many landholders spent too little on rabbit control but relied on the rabbit fur and meat industry to do the work, or partly made up for foregone livestock production by harvesting rabbits.[53] As well, there are other problems in assuming that Australia would have rapidly followed New Zealand's lead in taking measures to eliminate rabbits. One of the reasons why greater attention was paid to rabbit control in New Zealand was the higher productivity of the land. The income foregone per hectare was less in Australia's relatively infertile pastoral lands.

The progressive de-commercialisation of rabbits in New Zealand between 1947 and 1952 removed the option of using the rabbit industry to partially control rabbits and forced farmers to seek a different economic balance.[54] Rabbits were generally brought to low densities by the late-1950s, greatly strengthening the economic position and stability of the livestock industries. By contrast, Australia in 1950 had yet to reach a decision on de-commercialising rabbits to ensure that national efforts to control them were not undermined by other agendas. As it turned out, myxomatosis circumvented those political difficulties, effectively removing the need for legislation. Even so, as data on the export of wild rabbit meat and skins show, the remnants of the Australian rabbit meat and fur industry persisted into the 1960s despite an immediate 60 per cent fall in numbers of rabbits processed when myxomatosis first spread.[55] Given this situation, it is unlikely that a solution to Australia's rabbit problem along the lines seen in New Zealand would have been implemented quickly. In all probability, there would have been a long time lag before any alternative rabbit control programme was set up. This means that our conclusions regarding the financial benefits of

53 Myers, A survey of myxomatosis.

54 Gibb and Williams, The rabbit in New Zealand.

55 Fenner and Fantini, *Biological control of vertebrate pests*, p. 25.

introducing myxomatosis into Australia are conservative because the situation presented in our 'without-biocontrol' scenario might have taken many years to be implemented.

With current technology, Australia still has a seemingly unavoidable economic loss to rabbits of about A$200 million annually.[56] This residual cost of rabbits is not related to Australia's large inland pastoral areas because myxomatosis and RHD have been particularly beneficial in such regions where there are no economically justifiable alternatives for controlling rabbits. Rather, the problem is most likely due to the fact that when rabbits were reduced to low levels, they were confined to areas that were difficult to treat (e.g. roadsides, creeks, and rocky hills) or rarely seen by land-managers during day-to-day activities and no longer considered a threat. Obvious damage on individual properties may not be enough to elicit reaction, but accumulated across an entire continent, still presents a significant tally. As a consequence, the residual losses that rabbits cause are not likely to be addressed by the livestock industries for socioeconomic reasons unless substantially subsidised. This is also an issue for conservation agencies because the areas where rabbits are hard to eliminate are often places where rabbits persist among remnant native vegetation and even at very low levels they can inhibit natural tree and shrub regeneration.[57]

To deal with these problems, new criteria for judging rabbit problems would need to be accepted by land managers and comprehensive programmes for eliminating rabbits would need to be applied on a landscape scale. In farming areas, for example, high levels of rabbit control on roadsides are economically attainable if several control methods are used in combination.[58] This involves relatively high initial expenditure, which is offset through very low maintenance costs in subsequent years.[59] Nonetheless, farmers should not be expected to meet the entire costs of protecting public assets such as native vegetation on roadsides and subsidies or other incentives are likely to be required to advance rabbit management.

Finally, the loss–expenditure frontier models developed here provide an initial framework for considering the economics of enhancing current biological control agents or releasing additional rabbit-specific pathogens. As the introduction of RHD showed, bringing a new agent into an environment where another biocontrol agent was already present resulted in a comparatively modest marginal benefit despite its capacity to cause over 90 per cent mortality in native rabbits.[60] Had it been the first disease introduced into Australia's rabbit population, its impact would have appeared far greater. In economic terms, it means little to try to apportion subsequent benefits to each agent when the net benefits are the main

56 Gong, Sinden, Braysher, and Jones, *The economic impacts*.

57 Myers, A survey of myxomatosis; Cooke, Rabbit control; Cooke, Jones, and Gong, An economic decision; Cooke, Rabbits.

58 Cooke, Rabbit control.

59 Cooke, Jones, and Gong, An economic decision.

60 Mutze, Cooke, and Alexander, The initial impact of rabbit.

interest. Nonetheless, the massive benefits achieved by releasing myxomatosis should not cloud the fact that subsequent investments of this kind can produce highly favourable benefit ratios. As an example, research leading to the introduction of RHD cost about A$12 million over 8 years and resulted in an immediate increase in benefits to Australia's livestock industries of about A$350 million annually.[61] Other advantages of new biocontrol agents, such as potential for use in areas where the current RHD virus is constrained by a benign endemic rabbit calicivirus or for improving rabbit control in arid areas, are also of critical importance.[62] They still represent a highly favourable return on investment and should not be ignored or considered trivial simply because they do not provide economic benefits on the same scale as myxomatosis.

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61 Saunders, Cooke, McColl, and Peacock, Modern approaches.
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