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Economic evaluation of the successful biological control of *Azolla filiculoides* in South Africa

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Abstract

Azolla filiculoides (red waterfern) is a floating fern native to South America which has invaded aquatic ecosystems in South Africa. Thick mats of *A. filiculoides* on dams and slow-moving water bodies cause economic losses to water-users. Affected water-users were surveyed using a questionnaire to assess the importance of the weed. Among those most seriously affected were farming (71%), recreational (24%), and municipal (5%) users. The average water area covered by *A. filiculoides* (per water-user) was 2.17 ha, with an expansion rate of 1.33 ha per year. The frond-feeding weevil *Stenopelmus rufinasus* was released as a biological control agent at the end of 1997. Within 3 years, the weevil had reduced the weed population to the point that it was no longer considered a problem in South Africa. Based on year 2000 data, the cost savings (per user per hectare) resulting from the biological control program included a reduction of on-site damages caused by the weed to the value of US$589 per hectare per year. The average cost per hectare per year for the biological control program for the period 1995–2000 amounted to US$278, excluding investment costs of USD$7700 in 1995. These historic costs and benefits were adjusted to constant year 2000 values. The predicted spread of the weed was calculated on the basis of a sigmoid-curve rate of spread model. The net present value (NPV) of the program was calculated from 1995 onwards and discounted at 8%. This resulted in a NPV of US$1093 per hectare and US$206 million for South Africa as a whole. For the year 2000, the benefit–cost ratio was calculated at 2.5:1, increasing rapidly to 13:1 in 2005, and 15:1 in 2010 as the costs of the biological control program are expected to decrease. These indicators reinforce the overall economic viability of biological control, but do not necessarily confirm the viability of biological control on each management unit itself. The results reflect the dynamics of biological control on site-specific survey information, and place higher benefit–cost ratios achieved in other national level studies in a better context. It also raises the important policy question of who is responsible to finance such control programs in future, because on-site benefits of control are enough to justify the program in its own right. The paper concludes with recommendations on a financial mechanism to address biological control of invasive species in a sustainable manner.

Keywords: Red waterfern; *Stenopelmus rufinasus*; Benefit–cost ratio; Net present value

1. Introduction

Azolla filiculoides Lamarck (Azollaceae) (red waterfern) is a small (1–2.5 cm) aquatic fern, which is native to South America (Lumpkin and Plucknett, 1980). The fern has, however, spread to many countries of the world where it is considered a weed (Ashton, 1974; Diatloff and Lee, 1979; Hill, 1999). It was first recorded in South Africa in 1948 in the Oorlogspoort River, Colesberg, Northern Cape Province (Oosthuizen and Walters, 1961), where it was introduced as an ornamental fishpond plant in 1947 (R. Randall, Cape Nature Conservation, Sedgefield, Eastern Cape, South Africa, personal communication). Initially, the plant was confined to the Colesberg area, but a combination of a lack of natural enemies, dispersal between water bodies by humans and possibly waterfowl, and phosphorus-enriched waters

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facilitated an increase in its distribution and establishment (Hill, 1998a). By 1998, the weed was recorded at 152 sites throughout South Africa (Henderson, 1999), with a conservative estimate of total water surface area covered of 334 ha.[1]

Azolla filiculoides formed dense mats (5–20 cm thick), on dams of up to 10 ha and on slow-moving water bodies. It seriously affected the biodiversity of aquatic ecosystems and had severe implications for all aspects of water utilization (Gratwicke and Marshall, 2001). These effects were considered to be most severe in the agricultural sector, where the weed increased siltation of dams and rivers, reduced the quality of water for agricultural and domestic use, clogged irrigation canals and pumps, and caused drowning of livestock that were unable to differentiate between pasture land and a weed-covered dam (Hill, 1997).

Control options for red waterfern were limited as mechanical removal was impractical due to the rapid rate of increase of the plant; the surface-area doubling time of *A. filiculoides* is 7–10 days (Lumpkin and Plucknett, 1982). Also, no herbicide has been registered against the plant in South Africa. Biological control was seen as the only viable long-term control option for this weed (Hill, 1997). In 1995, the frond-feeding weevil *Stenopelmus rufinasus* Gyllenhal (Coleoptera: Curculionidae) was imported from Florida (USA). Following host-specificity screening (Hill, 1998b), the weevil was released in December 1997. The results of the biological control program have been dramatic. The weevil has caused local extinction of red waterfern at the sites where it was released (McConnachie, unpublished data). In addition, the weevil has dispersed on its own (or via waterfowl movement) to many more weed-infested sites throughout the country. The rapid rate of establishment of the weevil and the devastating effect it has had on *A. filiculoides* in less than one year (McConnachie, unpublished data) means that the weevil has had a significant impact on the weed status of *A. filiculoides* in South Africa. Three years after the release of the weevil, the weed no longer poses a threat to aquatic ecosystems in South Africa and its effects on the utilization of water resources have been significantly reduced.

Biological control of weeds is generally considered successful when the target plant population has been significantly reduced and no additional control methods are required, as is now the case of *A. filiculoides* in South Africa. Success is usually described using ecological criteria, which are difficult to quantify, or descriptions of sociological or environmental benefits (Julien and White, 1997). The reduction of a weed can be measured in terms of an increase in crop production and/or reduced costs of other control measures (Julien and White, 1997). For example, where alligatorweed, *Alternanthera philoxeroides* (Mart.) Griseb. (Amaranthaceae), was locally controlled on a river in Australia, the local council saved A$8000 per year on herbicide applications (Julien, 1981). Such savings, however, have not always been quantified.

A commonly used procedure in the assessment of biological control projects since the early 1930s (Huffaker et al., 1976), is the calculation of benefit–cost ratios. The decision rule for this protocol implies that a biological control activity is economically viable if the ratio of the present value of benefits to the present value of costs exceeds one. Nevertheless, it should be noted that such a decision rule does not give information on the economic viability of possible alternative control projects, and these should ideally also be compared according to the same decision rule before selecting an option. An analysis on the cost-effectiveness of alternative control options, therefore, would be beneficial prior to calculating benefit–cost ratios to obtain the relative ranking of these control options. If one option is already more cost-effective than the alternatives, and it is expected that benefits would also be higher, a cost-effectiveness analysis would be sufficient to generate a ranking on which option to use. Benefit–cost calculations, however, have the additional benefit of expressing the costs of control in terms of the efficacy of control, and thus in terms of the potential economic losses that will be avoided.

The positive benefit–cost ratios for many projects indicate the effectiveness of classical biological control, and in some cases, indicate high economic viability (Table 1). These studies, however, cannot be compared directly with each other, unless the same cost and benefit categories were used. Despite these methodological differences, benefit–cost ratios have become increasingly important in describing the success and potential of the biological control method (Headley, 1985). The successes achieved with classical biological control, however, cannot always be depicted in terms of benefit–cost ratios. Often specific project costs and benefits are sketchy or lacking (Andres, 1977). A good part of this can be attributed to the difficulty of assigning values to the many intangible benefits and losses from the weeds themselves (Andres, 1977; Dahlsten et al., 2000) and the expected rate of spread of these species (De Wit et al., 2001). In addition, biologists often seek counsel from economists with experimental results that do not lend themselves to economic evaluation (Headley, 1985). This is evident in the methods of early studies (e.g., Box, 1960; Melville, 1959; Simmonds, 1960), which clearly focussed on the biology of the control effort rather than the economic details. Headley (1985) noted that without economic evaluation as an objective, scientific economic evaluation would continually fall victim to ad hoc procedures

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[1] 1 ha = 10,000 m^2.

Table 1
Examples of benefit–cost results of some successful biological control projects

Pest species controlled	Region	Date of control	Benefits/ annum (US$)	Costs (US$)	Benefit–cost ratio	Reference
Insects						
Diatraea saccharalis (sugarcane borer)	West Indies	1945	41,250	21,250	1.9:1	Box (1960)
Planococcus kenyae (coffee mealybug)	Kenya	1939	1,250,000	75,000	16.7:1	Melville (1959)
Aspidiotus destructor (coconut scale)	West Africa	1956	180,000	10,000	18:1	Simmonds (1960)
Ctenarytaina eucalypti (blue gum psyllid)	USA	2000	558,000–1,488,000	62,000	9:1 to 24:1	Dahlsten et al. (2000)
Weeds: terrestrial						
Opuntia megacantha (prickly pear)	South Africa	1950	237,500	42,500	5.6:1	Pettey (1950)
Xanthium occidentale (noogora burr)	Australia	1991	A$16,750,000	A$7,200,000	2.3:1	Chippendale (1992)
Senecio jacobaea (tansy ragwort)	Oregon	1996	16,200,000	1,200,000	13:1	Coombs et al. (1996)
Chrysanthemoides monilifera ssp. *rotundata* (Bitou bush)	Australia	2000	A$45,000,000	A$2,200,000	20.7:1	CRC (2001)
Weeds: aquatic						
Alternanthera philoxeroides (alligatorweed)	USA	1976	*	*	8:1	Andres (1977)
Salvinia molesta (Kariba weed)	Sri Lanka	1989	8 million	150,944	53:1	Doeleman (1989)

* Values not available. A$, Australian dollar.

to estimate the values of missing parameters. More recent studies (e.g., Chippendale, 1992; Coombs et al., 1996; CRC, 2001; Dahlsten et al., 2000; Doeleman, 1989), however, have followed methodical economic approaches in the calculation of their respective benefit–cost ratios. The aim of our study, was to determine the economic viability of the biological control program of *A. filiculoides* in South Africa.

2. Materials and methods

2.1. Questionnaire

We developed a questionnaire which was completed by personal visits with 30 randomly selected individuals/organizations affected by the fern. The questionnaire required data on the direct costs of the weed to the respondent. This included stock losses, the costs of replacing water pumps, the costs of setting up an alternative water supply, and the loss of recreational activities. The respondent estimated surface area of their water bodies and percentage infested. Duration of the infestation was also recorded.

2.2. Evaluating economic viability of biological control

The average costs per hectare per year of the weed per respondent was calculated from the questionnaire. As a result of biological control, these avoided costs (or benefits of control) were assumed to be constant for the time period 1995–2000 and adjusted to year 2000 South African Rands (ZAR) using Statistics South Africa's most recent producer price index (PPI). The costs to develop the biological control agent, including salaries, overheads, and operational costs were obtained from the Plant Protection Research Institute, Pretoria. These control costs were also adjusted using the PPI and expressed in constant, year 2000 ZAR. All amounts were converted to United States Dollars (US$) at a ZAR/US$ exchange rate of 10:1. The US$ figures were not adjusted for purchasing power or varying levels of income between the RSA and USA. Once these adjustments were made, average costs and benefits per hectare were calculated for the period 1995–2000. A rate-of-spread model was used to estimate the area that will be invaded with and without biological control in the future. This model is based on the well-known thesis that invasions occur on the pattern of a sigmoidal curve. Historic data points on the hectares that were invaded with *A. filiculoides* and the maximum that could be invaded on data produced in the South African Water Social Accounting Matrix (WSAM) was used to fit a statistically meaningful sigmoid relationship (David Le Maitre, CSIR Division of Water, Environment and Forestry Technology, Stellenbosch, South Africa, personal communication). A full discussion on the methodology can be found in Van Wilgen et al. (2003). It was assumed that the economic value of future benefits will increase at 3% per annum. It was further assumed that future costs of control will be 20% of the average costs during the period 1995–2000, a conservatively high figure for *A. filiculoides*, but one used as a proxy for the costs of maintaining biological control on different alien species in the future (Van Wilgen et al., 2003).

3. Results and discussion

3.1. Respondent demography

Of the 30 respondents, the majority were involved in farming (Fig. 1a). Recreational water-users was the next largest grouping followed by a small number of municipal users. Within the farming category, crop, cattle, and sheep farming were the main activities (Fig. 1b). Recreational water-users comprised mainly golf courses, ecotourism, hunting, housing estates, and fishing (Fig. 1c).

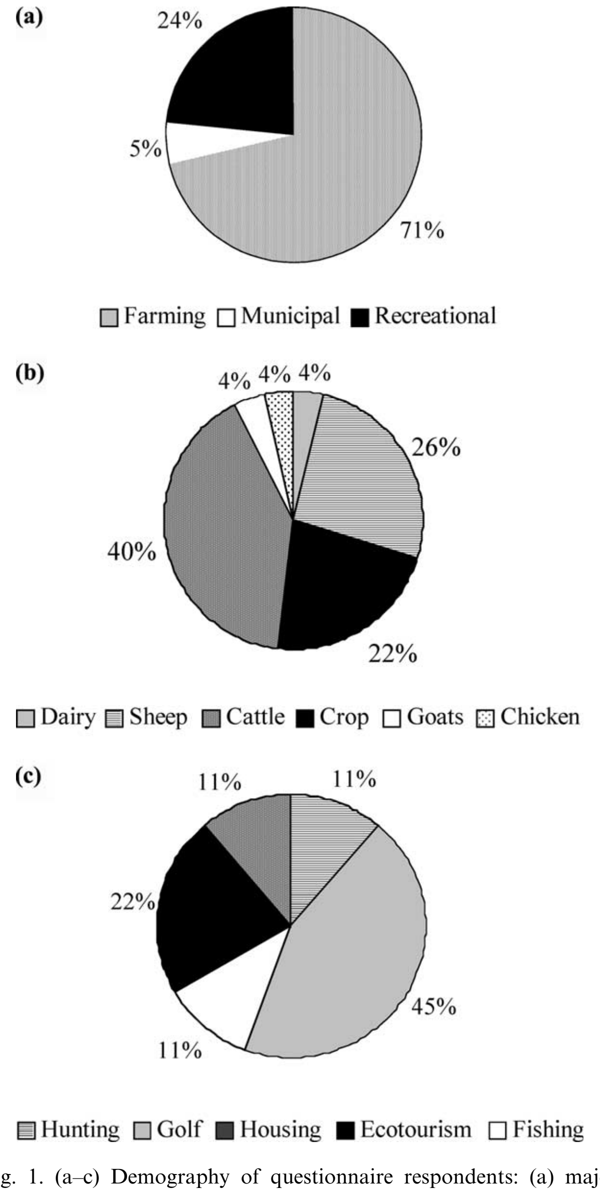

Fig. 1. (a–c) Demography of questionnaire respondents: (a) major activity of respondents ($n = 30$); (b) agriculture categories ($n = 21$); (c) recreational categories ($n = 9$).

3.2. Cost to respondents

Most of the 30 respondents had attempted to control *A. filiculoides* either manually using nets and rakes, or with the use of glyphosate-based herbicides. All were of the opinion that these attempts were futile due to the rapid regrowth of the weed. Losses to the agricultural community involved the replacement costs of irrigation pumps that had blocked and burnt out (at an average of US$63 per respondent per year) and the drowning of livestock (at an average of US$186 per respondent per year). One sheep farmer in the Free State Province estimated losses of 40 sheep per year (at US$30 per sheep), which had drowned after walking into weed-infested dams perceiving them as pasture. Red waterfern was found on many golf courses in South Africa. Course managers felt that they had incurred significant direct losses of customers and therefore income, due to aesthetic water features being covered by unsightly, thick mats of the weed. These and other miscellaneous costs (loss of property sales in housing estates bordering infested water bodies, labor costs to clean pump filters, loss of farming productivity, decline in recreational fishing, and helicopter monitoring of infested dams in game reserves) amounted to an average of US$533 per respondent, but should be interpreted with caution as the standard deviation is very high (Table 2).

The cost of constructing alternative water supply facilities is very high (Table 2). Most farmers found that livestock would not drink from infested water bodies as the weed gives water a bad odor. In addition, irrigation water was rendered unsuitable due to root material from the weed blocking sprinkler nozzles, and as a result farmers were forced to sink boreholes to ensure clean water supplies. In an extreme case, the town of Warden (Free State Province) was forced to construct an alternative water supply reservoir costing US$120,000. It is, however, not clear if these water works were constructed solely because of *A. filiculoides* impacts. As a result, a conservative approach was taken and final benefit–cost ratios were calculated without the costs of constructing alternative water facilities.

Increased water loss due to increased evapotranspiration from aquatic weeds has been recorded for other species (Brenzy et al., 1973; Boyd, 1987; Lallana et al., 1987). This is, however, not the case with *A. filiculoides* (McConnachie, unpublished data) and was therefore disregarded.

3.3. Cost of the biological control program

The total cost of developing the biological control of *A. filiculoides* using *S. rufinasus* for the period 1995–2000

Table 2
Summary of costs of *Azolla filiculoides* accruing to water-users, as determined by questionnaire

Assessment	Question	Mean response	SD	*n*
Water user	Total property size (ha)	2665	9619	29
	% of property covered by water	7	10	26
	Water use (liters/day)	258,963	644,799	21
Extent of weed	% of dam infested by weed	85	31	30
	Area covered by weed (ha)	2	2	30
	Time period of infestation (years)	5	7	30
	Azolla invasion (ha/year)	1.3	2	30
Costs		Mean response (US$)	SD	*n*
Current	Labour cost (mechanical control)	1004	1464	30
Control costs	Herbicide cost (chemical control)	134	3308	30
Damage costs	Damage to: Livestock	186	694	30
	Pumps	63	199	30
	Miscellaneous	533	2204	30
Replacement costs	Construction of alternative water facilities	7158	24,926	30
Total cost (including alternative water facilities)		7940	24,995	
Total damage cost (excluding alternative water facilities)		782	2024	
Azolla damage cost per hectare per year (excluding alternative water facilities)		589	7984	

Table 3
The total cost of developing and releasing *Stenopelmus rufinasus* against *Azolla filiculoides* in constant 2000 prices (1995–2000)

Cost type	Category	Value (US$)
Salaries	Proportion time/year on *A. filiculoides*	24,931
Infrastructure	Capital items	13,203
Survey costs	Travel and accommodation	8828
Total		46,962
Total area controlled (ha)		170
Average cost per hectare		276

was US$46,962 (Table 3) translating into an average annual cost of the weed of US$276 per hectare.[2] A total of 170 ha was controlled through this program. This is lower than the mean direct operational costs of alternative control reported by the respondents per year which amounted to US$1005 (mechanical control) and US$136 (chemical control) (Table 2). More than half of the respondents used both mechanical and chemical control, and it is apparent that these methods, or a combination of these methods, were not effective. This, basically, means that lower benefits are achieved at higher costs when these options are compared to the biological control option. It can be concluded that a biological control program on *A. filiculoides* is significantly more cost-effective than mechanical and chemical control options. On average, private welfare losses that could have been avoided through a biological control program of *A. filiculoides* did occur. As standard deviations are very high, such a conclusion would, however, need more site-specific analysis.

3.4. Cost–benefit analysis

With the exception of 1995, when no hectares of the fern were cleared by the biological control program, the average cost per hectare was US$276. When the investment costs of 1995 were added, the average costs for the 6 years (1995–2000) were US$1511 per hectare. As indicated by results from the survey, the average benefits per hectare of the biological control program over the same period amounted to US$450 per hectare. This analysis is not complete without referring to the present value of the future cost and benefits from a biological control program. When evaluated from 1995 onwards, with the inclusion of investment costs, benefit–cost ratios for the biological control of *A. filiculoides* increased from 2.5:1 in 2000, to 13:1 in 2005, and 15:1 in 2010. These results do not imply that it is beneficial to shift the focus from current to future control, but rather indicate that the value of economic losses that could have been avoided, would have risen substantially over time if nothing was done. The decision rule is based on whether the net present value (NPV) of a biological control program is positive. When the net benefit per hectare from 1995 onwards was calculated, the NPV is US$1093 per hectare. For the whole of South Africa, the NPV, also from 1995 onwards, of the biological control program is US$206 million. These positive values indicate

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[2] Excluding start-up investment costs of USD$7700 in 1995. These costs were excluded to make them comparable to the operational costs of alternative options of mechanical and chemical control.

the savings from the *A. filiculoides* biological control program.

3.5. Sensitivity analysis

As high standard deviations were recorded for the questionnaire data, sensitivity analysis was required. When the standard deviation of *Azolla* damages per hectare (US$7984) was used in the analysis, the damages increased to a NPV of US$122,147 per hectare and a NPV of the biological control program to the country as a whole of US$2.9 billion. When data of the landowner with the lowest reported damages were used as the baseline for the analysis, the NPV was negative US$8106 per hectare and a loss of US$3.1 million to the country as a whole. These figures indicate that one should interpret the results with caution. On average, biological control will benefit the country, but extreme variations can be expected at a site-specific level. This means that, on a national level, the financing of this biological control program was justified, but that such a program could possibly have been implemented at higher benefits if better up-front prioritization of dealing with the problem on a site-specific level was possible.

Two aspects of this biological control project were unique in facilitating economic analysis. The first is the rate at which the weed was controlled. Succesful biological control efforts are not usually observed within the period of a year (Andow et al., 1997). All of the field sites in this project were cleared within a year of the release of the weevil at that site. Second, unlike terrestrial weeds, *A. filiculoides* occupies well-defined areas in rivers, lakes, and dams. This allowed for accurate estimation of the extent of the invasion of the weed. Unfortunately, some important components were unavoidably omitted from this analysis—mostly off-site and on-site biodiversity and water losses. Other attempts have been made to quantify various components of biodiversity in monetary terms (e.g., van Kooten and Bulte, 2000). The invasion of aquatic ecosystems by *A. filiculoides* is known to have negatively affected biodiversity (Gratwicke and Marshall, 2001). Blaaukranz Nature Reserve, one of the last remaining habitats of the eastern Cape rocky (*Sandelia bainsii* Castelnau, 1861; Anabantidae), an endangered fish, had become totally overgrown with *A. filiculoides*. The Albany Museum (Grahamstown, South Africa) launched a public awareness campaign to help manually remove the weed every week, using volunteers with tennis rackets. Due to the rapid regrowth of *A. filiculoides*, however, this removal was not sufficient to keep the site clear. Had the biological control project not been successful, *S. bansii* faced extinction. Despite these negative impacts on biodiversity, monetary values were not estimated for these impacts and therefore were not included in the calculation of the benefit–cost ratio.

Water is a scarce commodity in southern Africa (Versveld and Le Maitre, 1998), and any action that improves access to, and the quality of, existing water resources is likely to have a positive economic value. These impacts were also not taken into account.

There are no direct economic benefits from *A. filiculoides* that need to be included in the evaluation. Since rice is not grown in the region, the control of *A. filiculoides*, which is used as a green manure in Asian rice paddies (Lumpkin and Plucknett, 1980), has at this stage no apparent drawbacks.

The above impacts would only increase the benefit–cost ratios of biological control. When both on-site and off-site (market and nonmarket) values, most often external to the land-owner, are included, benefit–cost ratios can be much higher (e.g., De Wit et al., 2001; Van Wilgen et al., 2003). In this study, only direct financial costs, as borne by the land-owner, were used in the analysis and still demonstrate the viability of the biological control program.

The development of an economic approach to evaluating environmental management programs, plans, and projects is helpful when evaluating alternative methods of environmental management and policy. Although the limitations of cost–benefit analysis are well documented, it is still a very useful method to present the impacts of a project on the environment in a systematic way (Hanley and Spash, 1993). Through such an analysis, limited funds can be allocated more efficiently across competing environmental management alternatives, in this case alternative control programs for different species. Biological control projects can be ranked and compared with other means of control to provide a more comprehensive picture of where funds could be best spent to achieve maximum private and social welfare.

Now that the economic viability of a biological control program has been highlighted, the policy question remains: Who remains responsible for its implementation? In the case of *A. filiculoides*, and in most other cases where invasive species are controlled, the South African government carries the investment and operational costs of these programs, while benefits accrue to private, public, and communal land-owners, many water-users, and specific ecosystems. In a world of more needs than resources, such programs do carry an opportunity cost to the government. These are the benefits of the next best alternative investment foregone, so it can be argued that, given their economic viability, biological control programs should be self-financed. The important question is whether financial benefits are actually achieved, as is the case with *A. filiculoides*. It is apparent that land-owners are already willing to pay for alternative control options at higher costs and lower benefits than biological control options on *A. filiculoides*. While the control of *A. filiculoides* was remarkably effective, ecologically speaking, and most benefits have already been internalized, some lessons for other biological control programs do apply. For instance, there is certainly scope to further explore inventive financial mechanisms to ensure the sustainability of biological control projects. It is recommended that more research should be directed to the viability of creating a fund for the biological control of invasive species. Contributors would include government (possibly as a research and development provider), private land-owners, national and international institutions whose vision is to preserve the integrity of ecosystems, and those responsible for the spread of such invasive species in the first place. Once established, such a fund could play a crucial role in minimizing massive private and social welfare losses incurred by the spread of alien invasive species.

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