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Quantifying the social and economic benefits of the biological control of invasive alien plants in natural ecosystems

Brian W van Wilgen[1], S Raghu[2], Andy W Sheppard[3] and Urs Schaffner[4]

Invasive alien plants reduce ecosystem service delivery, resulting in environmental, economic and social costs. Here we review the returns on investment from biological control of alien plants that invade natural ecosystems. Quantifying the economic benefits of biological control requires estimates of the reductions in ecosystem goods and services arising from invasion. It also requires post-release monitoring to assess whether biological control can restore them, and conversion of these estimates to monetary values, which has seldom been done. Past studies, mainly from Australia and South Africa, indicate that biological control delivers positive and substantial returns on investment, with benefit:cost ratios ranging from 8:1 to over 3000:1. Recent studies are rare, but they confirm that successful biological control delivers attractive returns on investment, which increase over time as the value of avoided impacts accumulates.

Addresses
[1] Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Private Bag X1, Matieland, 7602, South Africa
[2] CSIRO Health & Biosecurity, Brisbane, GPO Box 2593, Brisbane 4001, Australia
[3] CSIRO Health & Biosecurity, Canberra, GPO Box 1700, Canberra 2601, Australia
[4] CABI, Rue des Grillons 1, 2800 Delémont, Switzerland

Corresponding author: van Wilgen, Brian W (bvanwilgen@sun.ac.za)

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Introduction

Classical biological control programs use scientifically selected, host-specific natural enemies, mainly plant-feeding arthropods or fungal pathogens ('agents'), to mitigate the impact of invasive alien plants. Risks associated with biological control are mitigated through well-established, global screening protocols based on risk analysis, which has reduced these risks to minimal levels [1]. Nonetheless, in an increasingly risk-averse world, biological control faces growing regulatory and risk perception hurdles, even though successful biological control is relatively cheap compared to conventional mechanical and chemical control, and it is sustainable. Using highly host-specific agents to control invasive alien plants is also in stark contrast [2–4,5••] to historic unregulated use of generalist vertebrate predators or herbivores in misguided attempts to control pests or undesirable vegetation [6–8]. Yet the term 'biological control' dates from these early activities and so is often perceived as extremely risky [9]. One way to overcome these misconceptions is to clearly describe the mandatory, internationally accepted screening protocols, and to rigorously assess the risks before the release of any biological control agent [1]. Biological control scientists have achieved an outstanding >100 year track record of safety by following these risk assessment procedures [4,5••,9]. For example, one study [3] (based on a review of hundreds of published papers, and interviews with experts) recorded that >99% of 512 agents introduced for classical biological control of invasive alien plants around the world have had no known significant adverse effects on non-target plants. The incidence of non-target attacks has also substantially decreased over the past century as screening methods improved, and most such incidences are 'spillover' effects on plants related to the target species, predicted by the screening methods before release, and where the effects decline as the target species is brought under control [5••].

Another approach would be to examine, in terms of economic or social outcomes, the benefits that arise from biological control. Biological invasions have economic and social consequences because they can substantially reduce the flow of ecosystem goods and services from invaded areas. Removing the alien species concerned would also have a cost, because the control measures have to be paid for. In this regard, control costs can be substantially reduced if an effective biological control agent can be found. Ideally, the value of benefits and costs of control should be known, and control should be undertaken only where a benefit:cost analysis predicts that the estimated value of avoided or restored costs would exceed the estimated cost of control, including any negative side effects of the control [10].

Economic estimates of the impacts of invasive alien plants generally come from quantifying agroforestry losses and control costs. However, biological control is increasingly being used to manage invasive alien plants in natural ecosystems to offset their impacts on the delivery of ecosystem goods and services [11]. Here we discuss recent advances in what is known about the impact of invasive alien plants on ecosystem service delivery, and the economic and social evaluation of these services, and we address the challenges for using this understanding to guide the selection of biological control projects into the future.

Impacts of invasive alien plants on ecosystem goods and services

The estimation of costs due to biological control faces some challenges. First, although it is well established that invasive alien plants have many potential impacts on nature and human well-being [12], our understanding of these impacts on the environment and economy remains incomplete [10]. Some impacts of invasive alien plants and, in the case of successful management, the benefits of avoided costs can be valued using market prices. In contrast, others, such as socio-cultural ecosystem services or biodiversity, which often supports the delivery of ecosystem services, are not easily valued. In those cases where costs are not well reflected by market prices, more holistic approaches such as stated preference or revealed preference methods can be applied [10,13]. Another challenge is that biological invasions are spatially and temporally dynamic. Thus, estimates of the costs avoided by management remain rather vague even if ecological and economic modelling is applied [14].

Some recent studies have nonetheless quantified the costs of invasion by alien plants. In South Africa, invasive alien plants reduced annual surface water runoff by over 2 billion m3, potentially rising to 3 billion m3 per year [15]. In the Rhône-Alpes region in south-eastern France, the human health allergenic effects of the invasion of natural European ecosystems by common ragweed, *Ambrosia artemisiifolia*, were estimated to be €9.7–14.0 million per year between 2008 and 2015 [16•]. In natural rangelands, invasion can lower the yield and quality of forage, reducing livestock production [17–19]. In other studies, the economic impacts of invasive alien plants (and thus the likely benefits from management) were assessed by considering the value of multiple ecosystem services [20,21] or by comparing the effect of invasions at different densities on the household incomes of rural pastoralists [22]. Another study [25] used the ecosystem service value (ESV) approach, and estimations of changes in land use and cover, to assess the relative contribution of an invasive tree on overall losses of ESVs at the regional scale; this approach built on the notion that decisions regarding the use of ecosystems should consider the full costs and benefits for the welfare of both current and future generations [23].

Despite growing understanding, much remains to be done before the impacts of invasive alien plants on the delivery of ecosystem goods and services can be accurately quantified, and a recent compilation of reviews revealed that understanding remains patchy [26]. For example, the impacts of invasion due to changes in flood and fire regimes have received little attention [27]. Similarly, knowledge of the impacts of alien invertebrates and pathogens on forests are based on a few studies, where the value of impacts is 'sometimes largely exaggerated' [28]. The spiritual value and aesthetic appeal of ecosystems is recognised as a cultural ecosystem service, but how this is affected by invasive alien plants appears subjective, intangible and unquantifiable [29].

Assessing the net economic value of ecosystem services

Given that there is some understanding of the biophysical impacts of invasive alien plants, the economic benefits of controlling their spread would best be expressed in terms of avoiding or restoring these impacts through the implementation of control measures. This can be done by comparing the stream of economic values from a set of ecosystem services under a 'business-as-usual' scenario, with no control, to a scenario where control is implemented [10,30]. Because invasive alien plants sometimes have benefits (e.g. timber, firewood or fodder for livestock) as well as negative impacts, it is important to determine the net value over time (i.e. the value of avoided damage minus the loss of benefits). The initial outcome of control may be negative (when benefits are lost, control costs are incurred, and the target plant is not yet under control), but a positive (and sustainable) net benefit can be achieved in the longer term when the target species is brought under control [10]. So, for example, while the net benefits of invasive *Prosopis* trees in South Africa were found in one study to be currently positive, a negative net benefit would arise in the near future as the tree continued to spread and negative impacts grew, indicating that the introduction of biological control would be warranted [31]. Similarly, an assessment of the relative value and harm associated with invasive *Acacia mearnsii* trees in South Africa indicated that a 'do nothing' scenario (with no attempts being made to control spread of the tree beyond the limits of plantations) would not be sustainable (benefit:cost ratio of 0.4), while combining physical clearing and biological control with the continuation of the commercial growing activities would deliver positive benefit:cost ratios [32].

Assessing returns on investment from biological control

Several studies have estimated the returns on investment from the biological control of invasive alien plants in natural environments, and these have been summarised for Australia [33], South Africa [34], and globally [35••]. Generally, when it works, biological control delivers positive, often substantial, returns on investment. The Australian study [33] estimated the benefit:cost ratio across all biological control projects for which the analysis was done to be 23:1. A recent unpublished update of this study by the Australian CSIRO found that some of these benefits had grown, as would be expected. For example, the updated benefit:cost ratios were 113:1 for Skeleton weed (*Chondrilla juncea*), 52:1 for Paterson's curse (*Echium plantagineum*), and 33:1 for Ragwort (*Jacobaea vulgaris*). In South Africa, various studies compared the costs of biological control to the benefits of restored ecosystem services, or avoided costs, and avoided ongoing control cost [34]. In all cases examined, biological control was estimated to have been beneficial in economic terms, with benefit:cost ratios ranging from 8:1 for the shrub *Sesbania punicea* to 3726:1 for invasive Australian trees in the genus *Acacia*. The more recent global review [35••] included the cases mentioned above, as well as others, noting that benefit:cost ratios ranged from 23:1 to 7405:1 for a mixture of impacts to agriculture, impacts to wildlands, or mixes of both types of impact.

Recent advances in understanding the economic outcomes of biological control

Studies on the social and economic outcomes of biological control programs are rare, with relatively few recent examples (Table 1). These studies illustrate a number of points. First, they confirm that successful biological control delivers very attractive returns on investment. Secondly, these returns grow substantially over time, as the benefits of avoided costs accumulate. It is therefore

Table 1

Findings of recent studies and their implications for estimating the economic and social returns from the biological control of invasive alien plants in natural ecosystems

Study	Findings	Significance
Estimating economic benefits of biological control of common ragweed (*Ambrosia artemisiifolia*) [16•]	Biological control is expected to reduce the annual medical health costs by between €9.7 and 14 million (10.8–15.5 million) USD) in south-eastern France alone.	Demonstration of a potential significant positive outcome of biological control in terms of human health
Quantification of the socioecological impacts of *Tithonia diversifolia* (Mexican sunflower) [36]	This species is widely promoted as a "green manure" in Zambia, but has significant livelihood and biodiversity costs.	Costs need to be considered by those actively promoting the use and further dissemination of the species, and opposing biological control.
Socio-ecological impacts of *Opuntia stricta* (Australian pest pear) [37].	Contributes to ill health and death of livestock in eastern Africa, and also impacts human health and mobility and reduces household incomes.	Provides clear motivation that biological control would be justified.
Global review of the economics of biological control for species invading wildlands [35••]	Provides an overview of economic outcomes of biological control, and discusses how biological control should be funded.	Stresses the need to document economic outcomes to support policy decisions about which species to target using biological control.
Economic analysis of ecosystem service benefits of water hyacinth management [38••]	Long-term control delivered a benefit:cost ratio of 34:1 over 38 years in Louisana, USA.	This study stressed the value of keeping long-term records to support robust economic analyses.
Development of a method to categorise the outcomes of biological control of invasive alien plant species [39•]	Uses South African examples to illustrate a system for categorising the long-term effects of biological control on invasive alien plant populations.	Having a robust, standardised method to rate the effectiveness of biological control will assist in assessments of economic outcomes. This study also stresses the value of long- term monitoring.
Review of the impacts of biological invasions on ecosystem services [26]	Provides a useful overview of what is known about impacts of plant invasions on a wide range of ecosystem goods and services.	Source of information on impacts that can be used to inform economic studies on costs avoided through biological control.
Economic impacts of biological control of *Cryptostegia grandiflora* (rubber vine) [40]	Control has delivered a benefit:cost ratio of 109:1 in Australia	Demonstration of positive economic outcome of biological control
Economic impacts of biological control of *Euphorbia esula* (leafy spurge) [40]	Control has delivered a benefit:cost ratio of between 8.6:1 and 56:1 in Canada and the USA	Demonstration of positive economic outcome of biological control; shows that benefits grow over time as the value of avoided costs accumulates
Economic valuation of the water-saving benefit of *Eichhornia crassipes* (water hyacinth) control [41]	Annual benefit due to water savings was estimated at between ZAR54 million-1.2 billion (3.7–81.6 million USD)	Highlights the need for invasive plant control, particularly in economically productive water resources
Water loss savings due to biological control of *Eichhornia crassipes* (water hyacinth) [42].	The benefit:cost ratio at the low evapotranspiration rate was less than one, but at the higher evapotranspiration rates the return justified the costs of biological control	Inclusion of the costs of damage to infrastructure, or the adverse effects of water hyacinth on biodiversity, would justify the use of biological control even at low transpiration rates

important to monitor impacts over a long period to be able to demonstrate these ongoing benefits. The use of questionnaire surveys is emerging as a valuable tool for assessing people's perceptions of impacts, and the results of these surveys can be used to justify the initiation of biological control in many cases. Also important is that people tend to forget how troublesome invasive alien plants had been once they are brought under control [45], and support for ongoing control can fade, with obvious negative impacts should control be discontinued.

Challenges for the future

While retrospective socioeconomic analyses of the biological control of invasive alien plants are useful, we need to move towards more proactive information-gathering in each biological control program. This will require (a) quantification of the biophysical impacts and benefits of invasive alien plants, (b) translation of these impacts into social and economic costs and benefits, and (c) investigation of the extent to which these impacts can be mitigated by biological and other methods of control [43,44]. Collectively, such information would enable an objective analysis of the extent to which biological control could mitigate the impacts of invasive alien plants and help explicitly quantify the returns on investment in different types of management. In addition to elucidating the value of biological control, such approaches may also enable a better communication of the risks, costs and benefits of biological control as a sustainable method of invasive alien plant management.

Conflict of interest statement

The authors have no conflicts of interest.

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