

A benefit-cost analysis framework for prioritization of control programs for well-established invasive alien species

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Abstract

Invasive alien species (IAS) are identified as a major threat to biodiversity and ecosystem services. While early detection and control programs to avoid establishments of new alien species can be very cost-effective, control costs for well-established species can be enormous. Many of these well-established species constitute severe or high ecological impact and are thus likely to be included in control programs. However, due to limited funds, we need to prioritize which species to control according to the gains in ecological status and human well-being compared to the costs. Benefit-Cost Analysis (BCA) provides such a tool but has been hampered by the difficulties in assessing the overall social benefits on the same monetary scale as the control costs. In order to overcome this obstacle, we combine a non-monetary benefit assessment tool with the ecosystem service framework to create a benefit assessment in line with the welfare economic underpinnings of BCA. Our simplified BCA prioritization tool enables us to conduct rapid and cheap appraisals of large numbers of invasive species that the Norwegian Biodiversity Information Centre has found to cause negative ecological impacts. We demonstrate this application on 30 well-established invasive alien vascular plant species in Norway. Social benefits are calculated and aggregated on a benefit point scale for six impact categories: four types of ecosystem services (supporting, provisioning, regulating and cultural), human health and infrastructure impacts. Total benefit points are then compared to the total control costs of programs aiming at eradicating individual IAS across Norway or in selected vulnerable ecosystems. Although there are uncertainties with regards to IAS population size, benefits assessment and control program effectiveness and costs; our simplified BCA tool identified six species associated with robust low

cost-benefit ratios in terms of control costs (in million USD) per benefit point. As a large share of public funds for eradication of IAS is currently spent on control programs for other plant species, we recommend that the environmental authorities at all levels use our BCA prioritization tool to increase the social benefits of their limited IAS control budgets. In order to maximize the net social benefits of IAS control programs, environmental valuation studies of their ecosystem service benefits are needed.

Keywords

benefit points, control measures, ecosystem services, eradication, invasive alien plants, prioritization

Introduction

The consequences of the overall threats and damages caused by invasive alien species (IAS) are growing (Vié et al. 2009; Early et al. 2016; Pyšek et al. 2020). The handling of such species is embedded in the United Nations sustainability goal number 15.8 committing to: “*introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species.... and control or eradicate the priority species*”. The damages of IAS have often been correlated with loss of biodiversity (Butchart et al. 2010; Powell et al. 2011; Dueñas et al. 2018; Linders et al. 2019), which in itself can be detrimental for sustainable and resilient ecosystems (Pyšek and Richardson 2010; Vilà et al. 2011; Gallardo et al. 2019) and thus have subsequent effects on supporting, provisioning, regulating and cultural ecosystem services (Vila and Hulme 2017). Even though IAS have been considered a threat to ecosystem services for decades, control programs tend to be implemented late in the invasion process, when such species are well established with large reproducing populations. Invasive species are not evenly spatially distributed and are often highly correlated with infrastructure (Huang et al. 2012; Dodd et al. 2016; Zhou et al. 2020) and trade (Westphal et al. 2008). In fact, nearly all introductions are caused by humans either intentionally, through for example horticulture (Drew et al. 2010), or unintentionally through ballast water, soil/timber import, transportation of goods etc. (Hulme 2009). The introduction pressure of alien species in general is projected to rise with increased globalization (Meyerson and Mooney 2007; Early et al. 2016; Seebens et al. 2018), and with climate change (Bellard et al. 2013, 2018). Many governments have therefore aimed at minimizing current and future threats by IAS through directed control programs. However, such programs have been difficult to implement due to steep economic costs (Rejmánek and Pitcairn 2002) as well as other societal factors (Reaser et al. 2020b). Several tools and recommendations have been proposed to help implement control programs (Genovesi and Carnevali 2011; Hulme et al. 2018; Reaser et al. 2020a, b; Verbrugge et al. 2021).

One of the main obstacles for implementing such control programs is their cost (Invasive Species Specialist Group 2001). Eradicating alien species prior to establishments (i.e., door knocker species) or alien species in an early stage of invasion reduce control costs. This has been coined “Early Detection and Rapid Response” (EDRR) (Westbrooks 2004; Reaser et al. 2020b), and such programs have proved to be highly

cost-effective. Although the EDRR approach is an important framework for future invasions, we are still left with the question of how we should best deal with all the IAS that established vast populations decades ago, and which negatively impact ecosystem services. With the large costs needed to eradicate or control an increasing number of well-established invasive species, and the increased competition for governmental funds in the age of the ongoing pandemic and climate change, it is more important than ever to document the social benefits in relation to the costs of IAS control programs. This calls for Benefit-Cost Analysis (BCA) (Boardman et al. 2018). While BCA is routinely used as a decision support tool to evaluate and prioritize governmental projects and programs in the transportation, environment and energy sectors in many countries (including the European Union and the USA) (OECD 2018), BCA has only recently been suggested for use in management of IAS (Hanley and Roberts 2019).

In Norway the recent “Action strategy against alien invasive species 2020–2025” (Ministry of Climate and Environment 2020) calls for assessments of benefits and costs of control programs. However, a main obstacle for large scale use of BCA, which requires monetary estimates for both benefits and costs, is the lack of economic valuation of the mostly non-market benefits of eradicating each of the nearly 1500 alien species found in Norway. There are few non-market environmental valuation studies of effects of IAS on biodiversity and ecosystem services we can transfer/generalize from, and non-monetary assessments tools including impact score systems such as GISS (Generic Impact Scoring System; Nentwig et al. 2016) cannot be used directly as they are not consistent with the welfare economic theory underpinning BCA. This paper aims at closing this gap by combining a GISS-inspired benefit point system with the ecosystem service framework (Millennium Ecosystem Assessment 2005) into a non-monetary benefit assessment based on the contribution to human well-being underlying BCA.

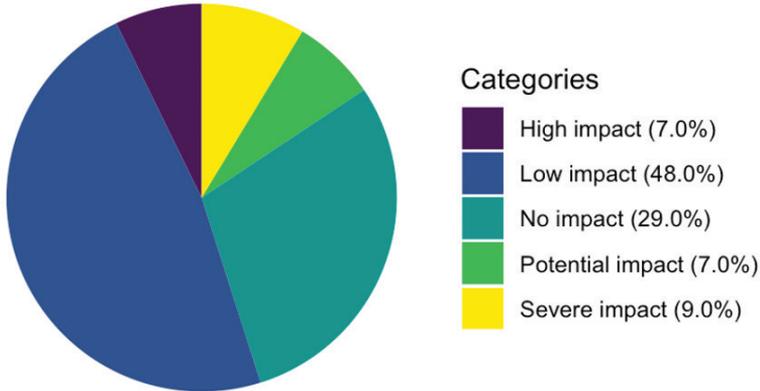
We demonstrate the use of this simplified BCA tool for well-established IAS by applying it to vascular plants in Norway. Although alien species can be found in many organism groups, vascular plants is by far the largest group of IAS in Norway; see Figure 1. Vascular plants are also predominantly found among the ecological impact categories (93% and 82% respectively) of alien species and impose high and severe ecological impact. Thus, we apply the BCA tool to 30 invasive vascular plants which impose severe to high impact on ecosystems. Our approach is carried out as a follow-up of the ecological impact assessment performed by the Norwegian Biodiversity Information Centre (NBIC), and the ecological input builds on the data included within the expert assessments embedded in the NBIC databases. Our approach therefore is a supplement, not a competitor to such ecological impact assessments.

Methods and data

Benefit Cost Analysis (BCA) and the Ecosystem Service (ES) framework

In BCA we consider all the costs and benefits to society as a whole: the social cost and the social benefits. Thus, BCA is often termed Social BCA or Social CBA (Boardman

A: Impact categories



B: Alien species

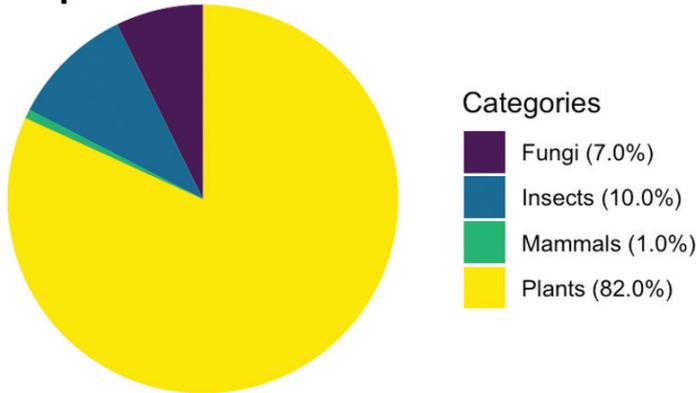


Figure 1. Invasive alien species (IAS) in Norway; distributed on different ecological impact category (A) defined as the assumed ecological impact by an alien species evaluated by the NBIC, and organism groups (B). Source: Norwegian Biodiversity Information Centre; NBIC (www.biodiversity.no).

et al. 2018). BCA is a policy assessment method that quantifies, in monetary terms, the value of all consequences of a policy to all members of a society and is rooted in economic welfare theory. The two main principles used to monetize social costs and benefits are the opportunity costs and individuals' willingness-to-pay, respectively. Valuation of market goods like labor and pesticides are based on (corrected) market prices, e.g., the market price for labor under full employment is the gross wages plus social costs of employment, whereas it is lower and equal to the opportunity cost when there is unemployment. Non-market goods like water quality and biodiversity are assessed using environmental valuation techniques applying the same principles (e.g., recreational value of angling and bathing) and non-use values (e.g., existence and bequest values of attaining good ecological status in lakes, which also accrue to people with no actual use of the lake). Hanley and Roberts (2019) state in their review of the potential for BCA to prioritize invasive species control actions that the economic benefits are not

limited to those associated with market-valued goods such as crops but should include increased exposure to disease and disruption to ecosystem service supply and impacts on biodiversity (Hanley and Roberts 2019).

The main challenge in applying BCA to evaluate and prioritize control programs for IAS is to value the social benefits of avoided damages to biodiversity, ecosystem services, and public health in order to directly compare social benefits to costs on the same monetary scale. Although environmental valuation techniques are now well developed (see e.g., Johnston et al. 2017), the number of studies valuing the social benefits of eradicating IAS is too small^{*} to be used for benefit transfer to value all or large groups of IAS (Johnston et al. 2021). Therefore, we aim at developing and testing a non-monetary valuation method for assessing the social benefits which utilizes current knowledge of the ecological impacts of IAS and is consistent with economic welfare theory underpinning BCA. A framework for assessment of these benefits which is consistent with economic welfare theory is the ecosystem service (ES) framework. Ecosystem services are defined as outputs, conditions, or processes of natural systems that directly or indirectly benefit humans or enhance social welfare (Millennium Ecosystem Assessment 2005).

Calculating social benefits

Attempts to construct such prioritization tools have been made, for instance by adapting the Project Prioritization Protocol (PPP; Joseph et al. 2009) to IAS and vascular plants (Dodd et al. 2017), and through the Generic Impact Scoring System (GISS; Nentwig et al. 2018). The GISS represents a semi-quantitative impact score system attributing points on a scale from 0 to 5 for twelve different characteristics of alien species. The main criteria are ecological and social effects, and there are six sub-criteria for each main criterion (Nentwig et al. 2018). Each of these sub-criteria are rated by experts and the points are then aggregated, resulting in a list of 149 species which Nentwig et al. (2018) present as a “worst alien species list”. An advantage of the GISS is the ranking of all the alien species based on total points across all criteria. It should be noted, however, that this ranking implies assessments of the importance of the different sub-criteria within the two groups, and weighting of ecological versus social criteria. Note that assigning no weight to each sub-criterion when aggregating is also an implicit weighting as each sub-criterion is then given the same weight. We use the system with separate sub-criteria reflecting ecological and other social aspects and a system with points for each sub-criterion for each species as an inspiration for developing our framework. Here, we more explicitly use the ecosystem services framework when assessing each IAS with respect to the criteria for each species, to ensure that the assessment is in line with the welfare theoretical foundation of BCA.

* Only 20 of the 5140 non-market valuation studies worldwide found in the Environmental Valuation Reference Inventory (EVRI) database (www.evri.ca; accessed June 2021) value the damages from IAS.

In our framework, the benefits of controlling the species are assessed based on the ecosystem services that are affected by the respective species, as well as whether the species impacts human health or infrastructure. The ecosystem services assessed are supporting (ecological impact and effects on endangered nature), provisioning (food, fiber/materials), regulating (pollination, water regulation, erosion) and cultural services which are related to the use values (recreation, aesthetic beauty) and non-use values (natural heritage). Although not all categories were found to be affected by the alien invasive species considered in our analysis, they can be relevant for other taxa, and are thus kept in the presentation of this methodology. For each benefit category, we assessed the benefits of controlling the species on a scale from 0 to 4. The scale used for each ecosystem service and the source of this assessment are shown in Table 1.

Calculating social costs

The first step in the cost calculations was to estimate the costs per decare (1000 m²) to carry out relevant control measures applicable for each IAS. One obvious part of the cost is the direct cost of carrying out the measure, for example costs of labor for weeding or other mechanical removal of the IAS and costs of inputs like pesticides. Other direct social costs include administrative costs, i.e., cost of surveillance after the control measures are carried out. The social costs of collecting taxes should in principle be added to the control costs that are publicly funded but are not included here. These social costs are in Norway assumed to add 20% to the control costs according to guidelines for Benefit Cost Analyses given by the Norwegian Ministry of Finance (Norwegian Ministry of Finance 2014). In some cases, the control measures themselves may have negative effects (costs to society) like environmental damage from using pesticides as a control measure, or in terms of lost benefits to those who value the IAS. The latter may be the case for horticulture species like *Rhododendron* (Dehnen-Schmutz and Williamson 2006) or other pretty and/or historical IAS. These costs are harder to estimate in monetary terms and make it more challenging to compare costs across control measures. Here, we have excluded such indirect costs and potential benefits of IAS, and calculated the direct control cost only, which in most cases dominate total control costs. The species included in our analysis are not known to have substantial benefits, and therefore omitting potential benefits is not thought to be important for our results. In other cases, the IAS are known to have potentially large benefits as well as negative effects on ecosystem services, human health and infrastructure, and in these cases the benefits on for example provisioning services such as pollination should also be included. It is possible within our methodology to include such benefits, either as monetary values, which would reduce the net costs to society, or as unpriced effects.

In some cases, there are several control measures available to eradicate an invasive alien species. The control measures include several forms of mechanical removal, use of pesticides, a mix of the two, as well as covering the ground and hot water treatment. Different measures usually have different costs. In cases with several alternative control measures, we have evaluated all of them and included them in the cost ranges for the

Table 1. Benefit assessment of controlling invasive alien species (IAS) in terms of avoided damages to ecosystem services (ES), human health and infrastructure. Description of the benefit point scale (0–4) and data source used for each benefit category are provided within the table. Two categories were found to have no effect based on the 30 IAS included in this study: the provisioning service “fibers/materials” and regulating services in general. Source: Modified from Magnussen et al. (2019).

Benefit category	Benefit point scale					Source
	0	1	2	3	4	
1. Supporting ES: 1.1 Ecological impact	No known ecological impact (NK)	Low ecological impact (LO)	Potential high ecological impact (PH)	High ecological impact (HI)	Severe ecological impact (SE)	NBIC* Alien Species list
1.2 Effect of IAS species on threatened ecosystems	Intact (LC)	Near threatened (NT)	Vulnerable (VU)	Endangered (EN)	Critical (CR)	NBIC* Alien Species list/ Norwegian Red list for ecosystems
2. Provisioning ES 2.1 Food	No effects	Small effects, i.e., some reduction in area/production	Somewhat larger effects, i.e., large reduction in area/production/ grazing area	Large effects, i.e., large reduction in area/production/ poisonous for grazing/livestock, etc.	Very large effects, i.e., very large reduction in area/production/ Deadly for livestock etc.	Expert assessment*
2.2 Fiber/ materials	No effects of species in our analysis Benefit point scale not developed					
3. Regulating ES	No effects of species in our analysis Benefit point scale not developed					
4. Cultural ES 4.1 Recreation, aesthetic values	No effects	Minor changes in landscape. Small plants, low visibility, not restricting recreational activities	Aesthetic disturbance of landscape, not restricting recreational activities	Aesthetic disturbance of landscapes, restricting activities in areas but not growing in typical recreation areas	Aesthetic disturbance of Landscape, Restricting recreational activities	Expert assessment*
5. Human health	No effects	Discomfort / Indirect effects		Poisonous to humans	Deadly to humans	NBIC* Alien Species list, Expert assessment*
6. Infrastructure	No effects	Indirect effects (obstruct vision/ signs along roadside)			Severe damages to buildings, roads and other infrastructure	Expert assessment*

*The expert assessments are made by researchers at the Norwegian Institute for Nature Research (NINA)

*NBIC = Norwegian Biodiversity Information Centre (www.biodiversity.no)

IAS removal. However, all control measures are not applicable for all areas, for instance the use of pesticides might be precluded in nature conservation areas. Hence, it must be made clear which method is most cost efficient in different types of areas. The time it takes for the measures to effectively remove the IAS also varies across measures and species, and so does the need for follow-up measures after the initial treatment. We have made assessment of these aspects for each IAS and control measure. However, it should be noted that there is large uncertainty in these assessments of social costs because of limited systematic experience with different control measures for many of the IAS considered here. In accordance with standard procedure in BCA, we calculated the present value of the control costs for all affected parties, that is the aggregated social costs of all measures carried out over the time period needed for the eradication meas-

ures to be 100% effective. Typically, a huge initial effort with corresponding high costs is necessary for the first year or two to eradicate the IAS, followed by a much lower level of annual costs for a varying number of years.

The next step was to calculate the costs for different types of areas and the total area that needs control measures to eradicate the IAS. Based on the calculations described above, we chose the control measures that provided the lowest cost per decare in different types of areas where the IAS should be eradicated. We calculated the total cost of eradication stepwise, first across Norway, then in selected parts of Norway and/or in selected vulnerable ecosystems. Here, we utilized information on the effect of control measures, the total area where the IAS is found, and expert assessments of the density of IAS in different ecosystems; as recorded in the “Alien Species List” and “Alien species observations” in NBIC, respectively. For some IAS, scarce information on the prevalence in different ecosystems precluded estimation of the size of the areas in need of control measures. This prevented the estimation of total costs for these IAS, and they were therefore not included in our analysis.

BCA prioritization tool

In Table 2, we compare benefits and costs for control measures aimed at a hypothetical alien vascular plant species, with the aim to eradicate the species in a geographically limited area. To reach the goal, control measures will be carried out in an area of 2000 decare within an endangered ecosystem. We use the calculated costs per decare for the most cost-effective control measure which is applicable to the IAS and area in question. Then, we calculate the total cost of eradicating this IAS for the specified area; and assess and assign benefit points within each benefit category. Finally, we compare total control costs to total benefit by constructing different cost-benefit ratios.

Table 2 shows the costs of a specific control program for species A, the number of benefit points from the avoided damage to ecosystem services, and the size of the area for eradication. The last three rows in Table 2 shows three different ways of comparing the monetary costs and the non-monetary benefits. The simplest way is to summarize benefit points and total costs without comparing them in terms of cost-benefit or benefit-cost-ratios. This results in an illustration of control costs, benefits provided, and the overall importance of the benefits (expressed as the total number of benefit points). This procedure may work well in assessing different control measures for each individual IAS. However, it would be very demanding to rank 30 or more species and 1–2 control goals per species only by visual inspection of total benefit points compared to costs. Therefore, we have constructed three alternative composite measures comparing total costs to benefits (see the last three rows of Table 2). These are: (i) total cost per benefit point, (ii) control costs divided by the number of benefit categories with 4 benefit points (if one does not want to aggregate all benefit points, or do not agree with the scale for benefit points for each benefit), and (iii) including the size of the area of control in the costs per benefit point. Although the latter might be a good idea, it is far from obvious how this should be done.

Note that the method where benefits points are aggregated implies that we implicitly assign the same weight to all benefit categories. This means that avoided damage

Table 2. Illustration of IAS BCA tool. Control costs of eradication programs and benefit points (BP) for avoided ecosystem services (ES) damages (according to the methodology in Table 1) for a specified control program for the hypothetical invasive alien species (IAS) «A».

Species «A»		Qualitative description/comments
IAS control program goal	Eradicate species A from 2000 decarees of endangered ecosystems	
Costs		
Cost per decare	150 USD per decare	
Total cost	150 USD per decare x 2000 decarees = 300 000 USD	
Benefit types		
Benefit points (BP)		
Avoided negative ecological impact (non-use value)	4	The species is in impact category SE (Severe negative impact)
Avoided damage to endangered ecosystems (non-market / non-use value)	4	The species is eradicated in areas with CR (critically endangered) ecosystems
Avoided damage to food production (market / use value)	0	No effect
Avoided damage to fibers and other non-food provisioning ES (market / use value)	0	No effect
Avoided damage to regulating ES (non-market/ non-use value)	0	No effect
Avoided damage to cultural ES: recreation and aesthetic services (non-market/ use value)	4	The species is eradicated in areas where it is a nuisance to recreational activities and landscape aesthetics.
Avoided damage to human health (market and non-market/	0	No effect
Avoided damage to human infrastructure (market / use value)	0	No effect
Total benefit points (BP) of avoided damage	12	
Total cost per BP	300 000 USD/12 BP = 25 000 USD/BP	
Total cost per (number of ES with full score i.e., 4 BP)	300 000 USD/3 BP = 100 000 USD	
Total cost per (BP * controlled area)	300 000 USD/ (12 BP x 20 000 decare) = 1.25 USD per BP x decare controlled	

to infrastructure in a certain geographic area is weighted equally to non-use values e.g., avoiding damages to endangered ecosystems in the same area. Alternatively, one could aggregate the different benefit categories by assigning different weights to different categories, for example by weighting effects on the non-use values of damaged endangered ecosystems to be ten times higher compared to the effects on infrastructure. However, we have no information for assigning a specific set of such weights, and thus do not do this here. According to the principles of social BCA, the weights of these benefit categories should ideally reflect the preferences of the people whose wellbeing/utility is affected by the IAS. However, these weights can only be derived in monetary terms by applying revealed and stated preference techniques to derive people's preferences and willingness-to-pay and thereby avoid the damages caused by IAS on e.g., ecosystem services. As both revealed and stated preference techniques elicit the preferences of people in local communities, their preferences will be included, but participatory approaches and social impact assessments could also be used to elicit people's preferences (Frank et al. 2015; Moon et al. 2015; Crowley et al. 2017). One could involve experts and/or communities in this weighting process, which could influence the results. It is also worth noting that the total number of benefit points for each species, will depend on how many and

which benefit categories are included and assessed in the framework. The system is open and transparent, and thus makes it possible to test how sensitive the results are to the number and definition of each benefit category and the benefit points scale used.

Data collection

We have collected data from several sources. We have used observational citizen science data from the Norwegian species map service hosted by the Norwegian Biodiversity Information Centre (NBIC; www.biodiversity.no). The databases are based on a citizen science approach where data points can be added by either experts or lay people. However, it is partly quality controlled and curated by experts. Such citizen science data have proven to be of great value in biodiversity monitoring (Pocock et al. 2018). However, systematic variation in taxonomic coverage and geographic areas covered have been noted in such programs (Chandler et al. 2017). Still, data collected in this way has also been demonstrated to be high-quality non-biased data containing similar properties to data collected by scientists (Lewandowski and Specht 2015; Petrovan et al. 2020). The 30 IAS included in this study are conspicuous and easily identified, and therefore probably neither wrongly identified nor overlooked. An uncertainty-range was previously estimated for each of the IAS species within the NBIC database, based on expert judgment (Sandvik et al. 2020). Each data point within the NBIC database represents either an individual species or, more likely for IAS, a population. Three experts on the respective 30 species estimated individually the size of the area one location of the different species normally covers. After agreeing on the spatial size, the area was summed up across Norway based on the number of points per species respectively. These area estimates are uncertain due to the lack of systematic mapping of all IAS across the country. Also, some points may be invalid due to eradication or death. Thus, the size of the total area needed to be controlled contains uncertainty. However, we think our approach produces sufficiently large total control areas for eradication measures to be effective. For assessing ecological impact, we have used the evaluations from the Norwegian Biodiversity Information Centre (2018) where an expert panel evaluated 1473 alien species using the methodology described in Sandvik et al. (2012, 2019). Data for estimating control costs and eradication efficiency were based on previous cost estimates derived from municipality data and county officials (Blaalid et al. 2018). Benefit points were assessed partly based on information from NBIC and partly on expert judgments; see Table 2 for details.

Results and discussion

Estimation of total costs for control measures

We have estimated (i) costs per decare and (ii) total costs for eradication of each of the selected 30 vascular plant species (see list in Suppl. material 1: Table S1). Due to

lack of data, cost/benefit ratios for two of the 30 species within this study, *Eutrochium purpureum* and *Solidago canadensis* were not calculated (N=28). Eradication costs and effects are calculated based on previous cost estimates gathered from eradication projects and expert assessments on plant biology and traits, carried out by a group of three individual plant biologist. These costs are uncertain due to two factors: i) lack of documented effects of IAS control programs across space and time, and ii) uncertainties whether the number of observations reflects the population size and distribution of each of the species. The latter is the main contributor to the overall uncertainty. Our results show that there are large variations in eradication costs for the 30 IAS included here. Note that the vascular plants chosen is not a random sample, but comprises species identified to constitute severe to high ecological impact by the Norwegian Biodiversity Information Centre. Figure 2 shows that nine plants (all herbs) have relatively low eradication costs of less than 10 million USD, nine plants (mixture of herbs and woody plants) have medium eradication costs (10–100 million USD) and ten plants (mixture of herbs and woody plants) have high eradication costs (more than 100 million USD). In the latter group, four species, have extreme eradication costs (>1 billion USD), in which three of them are *Reynoutria* spp. These plants are known for their extreme high decare control costs, as they have very deep root systems and aggressive vegetative reestablishment. This makes eradication both difficult and expensive. It is important to note that the species included in this study share characteristics such as: (i) they are mostly assessed as having severe negative ecological impact (SE-species), (ii) they are relatively well-established, often through their use in horticulture; and (iii) most of them have additional negative effects on vulnerable (red-listed) ecosystems and/or species. Some species, such as *Lupinus* spp. have also been planted deliberately due to potential positive effects. *Lupinus polyphyllus* was considered a highly attractive choice for vegetation cover alongside new roads, and was often planted to prevent erosion, and for its ornamental value as it is both colorful and willing to germinate. Currently, this species has over 50,000 records within the map services of NBIC, making nationwide eradication highly unlikely. This is reflected in the calculated eradication costs of more than 20 million USD given that it is only eradicated in areas where it is a threat to red-listed ecosystems. Notably, its close relatives, *L. perennis* and *L. nootkatensis* have far lower associated eradication costs; less than one million USD. This can potentially be ascribed to their smaller number of records. It is important to note that we here assume no conflicts during the control process such as private landowners opposing eradications, and that all populations of each IAS are identified and successfully removed. Thus, we assume the control measures to be 100% effective. Despite the relatively low number (30) of vascular plant species assessed here, a general pattern in total eradication costs seems to emerge: Species with (i) large distributions or (ii) woody plant species are associated with higher eradication costs.

There are substantial differences in the upper estimates for costs for the different species, which is largely due to differences in the estimated area of distribution, but also differences in the control costs per decare. The knotweed (*Reynoutria* spp.) and fly honeysuckle (*Lonicera caerulea*) stand out, as the upper estimate of costs for measures

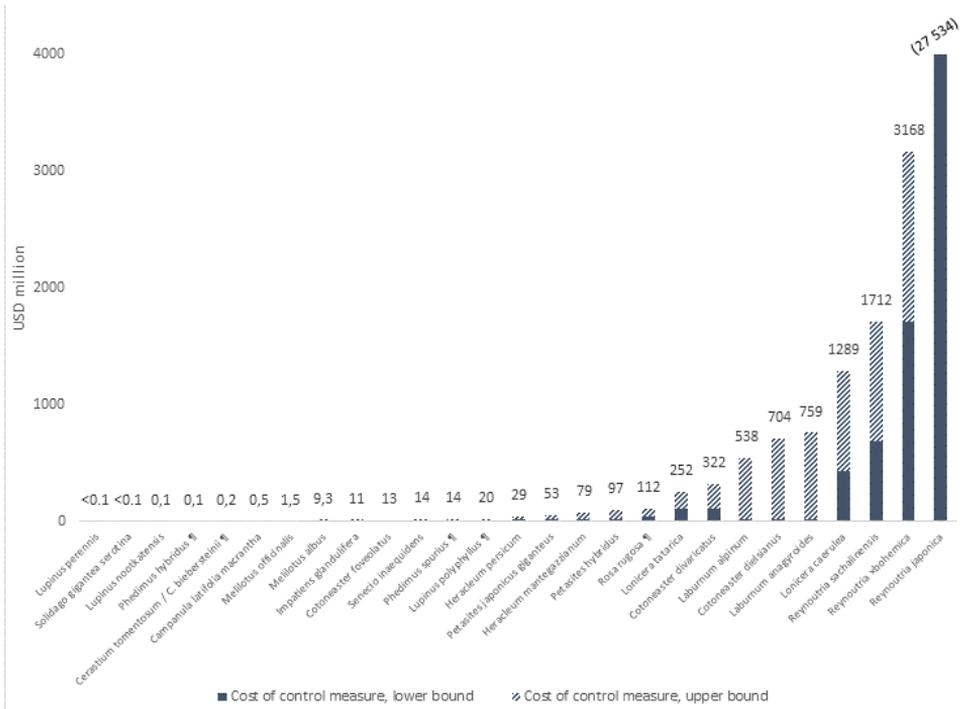


Figure 2. Total social costs (i.e., present value in million 2019-USD), upper and lower bound, of control measures for each invasive alien species (IAS), ranked in terms of increasing costs from left to right. For most species, the control costs would eradicate the IAS in all of Norway, but for five IAS (denoted ¶) the control costs are estimated for eradication in vulnerable ecosystems only, as this is considered to be the most realistic control program for these five species. The number in parenthesis implies the number is far above the scale of the y-axis. Converting Norwegian Kroner (NOK) to US dollars (USD), we have for simplicity used the approximate Purchasing Power Parity corrected exchange rate of 1 USD = 0.1 NOK. (<https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm>).

is considerably higher (more than USD 1,200 million) compared to the remaining vascular plant species. For all but five species we have estimated the costs of total eradication of species populations within Norway.

Assessment of benefits for control measures

The benefits of eradicating each of the 28 species were calculated using the benefit point scale for affected ecosystem services shown in Table 1. The total benefit point score for each species, and the ecosystem services that is affected, is shown in Figure 3. All species are identified to have severe or high ecological effect (NCBI) and are thus given similar score within the supporting ecosystem service category (i.e., category 1 in Table 1). The variation in benefit points for other ecosystem service categories are larger, but overall, most species also score benefit points within “Endangered ecosys-

tems” and “Recreational/aesthetic impacts”. Both the *Laburnum* spp. and *Heracleum* spp. are given higher scores within the “Human health” category as they have documented harmful effects in addition to high scores within all categories, which gives them overall higher benefit points compared to the remaining species. The *Reynoutria* spp. has been given points in the “Infrastructure” category, as they obstruct vision and signs along roads in Norway (Blaalid, pers. obs.).

Assessment of benefits and costs for control programs

Comparing costs and benefits of the control programs is not straightforward as costs are measured in monetary terms while the benefits are measured in “benefit points”. The data reveals that some species with high total costs have few benefit points, whereas other species have low costs but many benefit points. Some species can be controlled for a relatively low cost, while the benefits are likely to be quite large, as in the case of wild perennial lupine (*Lupinus perennis*) and narrow-leaved ragwort (*Senecio inaequidens*). It is less obvious that control measures should be undertaken for species such as *Reynoutria* spp. and *Lonicera* spp. as they have relatively high costs compared to the expected benefits. However, public and private developers as well as the public administrations at the municipal and county level will have to adhere to national laws and regulations for the handling of soils where alien species are present, for example in connection with road construction projects, even when costs are very high (Ministry of Climate and Environment 2015). Figure 4 depicts the comparison between costs and benefits of a control program in terms of costs per benefit point for each IAS, with the upper panel showing those with control costs (in million USD) per benefit point below 10, and the lower panel the IAS with the cost/benefit ratios above 10. This way of combining costs and benefits enable us to rank the IAS in terms of which species will be cheapest to control relative to a non-monetary measure of benefits. Uncertainties in both control costs and the benefit measure may affect the order of ranked species; however, with such a large span in costs, it will potentially affect closely ranked species. Testing it further across taxonomic groups of IAS will give a better resolution of this BCA tools robustness. Our results show that the species to the left in the upper panel of Figure 4, with low costs relative to the benefits including *Lupinus perennis*, *Lupinus nootkatensis*, *Solidago gigantea serotina*, *Phedimus spurius*, *Cerastium* spp. and *Senecio inaequidens*, should be given priority when allocating funds to control measures for the invasive alien vascular plant species considered here.

Notably, our BCA tool does not include the costs of preventing potential re-invasions after eradication. De facto re-invasions, defined as another event compared to un-successful eradications, are less likely given that the species have been successfully removed from the country, and may thus be subjected to a new BCA analyses with updated parameters. However, in cases where re-introductions are expected (e.g., cases where IAS species are removed from a given area) costs of preventing re-invasions are important to account for and should be assessed in future studies.

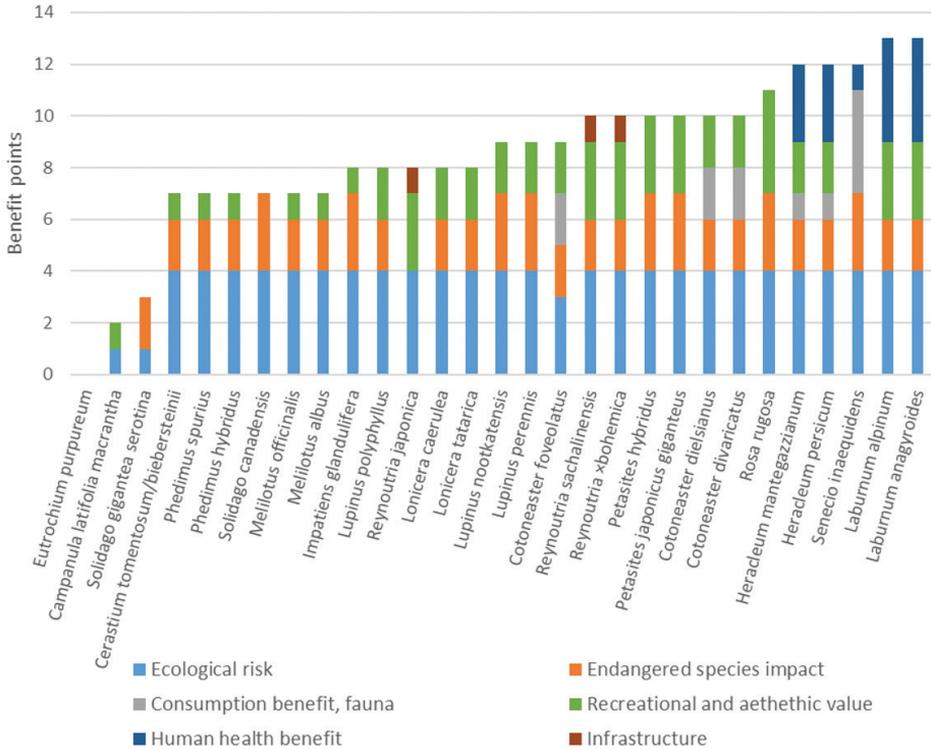


Figure 3. Benefit points (BP) of control measures for invasive plant species in Norway; total BP and for each benefit category.

Conclusions and recommendations

BCAs of eradicating/controlling different IAS provide vital information to policy makers and practitioners that can be used to rank IAS, and through this maximize the social benefits for a given control cost budget. However, the large number of IAS prohibits complete BCAs of different control programs for each individual IAS as it is difficult and time consuming to assess all social costs and benefits. The costs of controlling the different IAS are difficult to assess; not only due to uncertain costs of the different control measures themselves, but also due to incomplete information about the effectiveness of the control measures and which measures, or combinations of measures would suffice to control the IAS in question. In addition, there are uncertainties regarding the total distribution of IAS species in question.

Previous studies have identified lack of legal frameworks (Smith et al. 2014), lack of knowledge and variation in knowledge interpretation (García-Llorente et al. 2008), and lack of public support (Vane and Runhaar 2016) as main obstacles for implementation of control measures for IAS. Most of the 30 invasive alien vascular plant species considered here are species known to be included in control programs by municipalities and

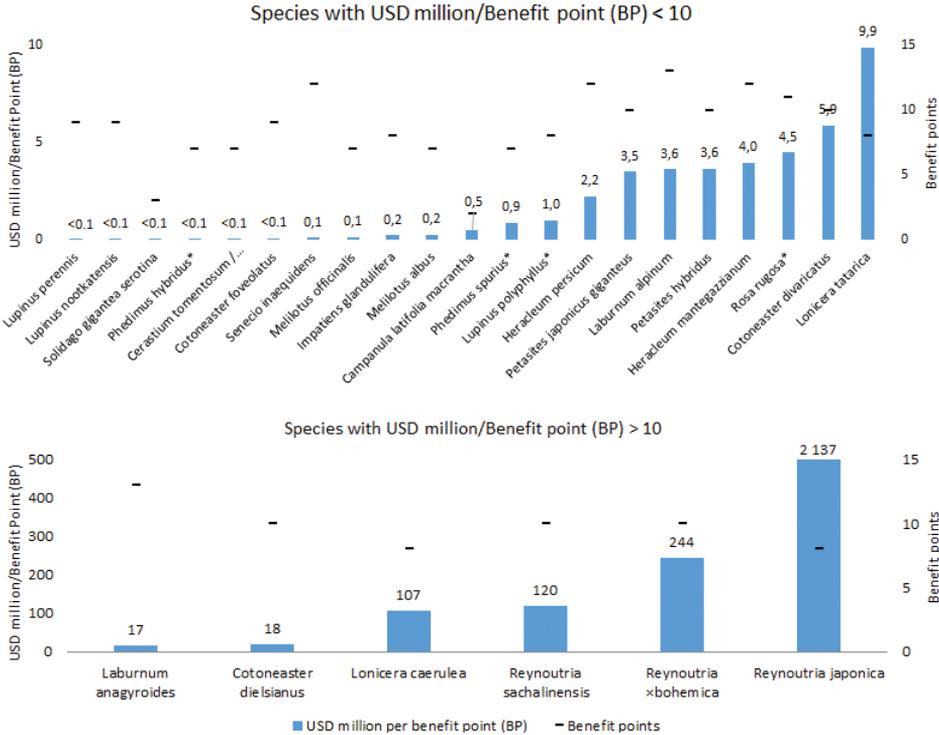


Figure 4. Control cost measures per benefit point (BP) for each invasive alien species (IAS) Average total cost of control measure in million USD divided by total BP. The upper panel and lower panel show the results for IAS with total cost (in in million USD.)/BP being larger and smaller than 10, respectively. N=28, as control costs were too uncertain to estimate this cost/benefit ratios for two IAS, *Eutrochium purpureum* and *Solidago canadensis*.

environmental authorities at the county level (Blaalid et al. 2018). Their status at the national alien species list in Norway states they have severe to high ecological impact. Therefore, they are all potentially candidates for eradication or control programs. However, our results clearly demonstrate that this is not feasible due to the huge economic costs. Currently, 10–20 million USD are used annually for control programs in Norway (Magnussen et al. 2014), and Figure 2 shows this would cover the costs of eradicating only a few of the 30 species at the national level in the next few years (see Figure 2).

Notably, our results indicate that the current IAS control budgets in Norway provide relatively small benefits per dollar, as over 50% of the resources are allocated to *Reynoutria* spp. and *Heraclium* spp. (Blaalid et al. 2018). We demonstrate how using our simplified BCA prioritization tool could aid environmental authorities at local, regional and national levels in spending their limited budgets to obtain higher benefits, potentially eradicating species within an area, compared to just preventing further spread. While BCAs have been performed for one or a few IAS in specific case studies (see e.g., Roberts et al. 2018), and theoretical models for economic optimal prioritiza-

tion of larger numbers of IAS have been developed (Courtois et al. 2018), there is, to our knowledge, no applied BCA tool to prioritize among the large number of species of alien invasive vascular plants as considered here. The prioritization tool we develop serves as an attempt to develop a simple BCA tool tailored to assess control of large numbers of individual IAS at relatively low costs. We estimate the average cost of applying the BCA tool to an individual IAS to be about 1,500–2,500 USD. Further, as opposed to the PPP and GISS assessment methods it uses the ecosystem service framework, which is a well-established and acknowledged way of assessing impacts on human welfare from changes in the ecosystems, and thus adhere to the welfare economic underpinnings of BCA. We should be careful in directly transferring and generalizing the results from this study across countries and other groups of IAS as there are large variations in awarded benefit points for a single species due to the variation in impact at the regional level. For example, we suspect that *Reynoutria* spp. would be awarded higher benefit points within the category “infrastructure” in Great Britain, as this plant is here known to destroy asphalt roads through erosions and even disrupt housing foundation (Fennell et al. 2018), illustrating that benefit points associated with individual plants may alter with space and time. Control costs can also vary across countries, e.g., labor costs in mechanical removal of plants in Norway may tend to be higher compared to many European countries and the US.

One of the main challenges for control programs of IAS is the funding scheme and the lack of interagency budgeting (Reaser et al. 2020a). Although we should aim at reaching an understanding and collaboration between organizations dealing with IAS control programs, the use of the BCA approach may overcome such obstacles as the benefit points can be compared to the cost at the national or regional level to establish an overall priority list. The simplified BCA prioritization tool described here, relies on both ecological and economic knowledge, and contributions from several disciplines are needed to reach sound prioritizing and management of invasive alien species. Benefits of eradicating alien species have often been estimated in terms of e.g., crop losses valued at market prices, without due consideration to non-market ecosystem impacts. This would easily underestimate the social benefits of invasive species control measures. More environmental valuation studies of avoiding damages to ecosystem services, will provide estimates of people’s preferences which is the ideal way to aggregate benefits of IAS control in BCAs. Meanwhile, our simplified BCA tool with no need for monetary assessment of benefits provides a cost-effective tool for constructing a priority list determining which IAS to control among a large number. It still provides a ranking of IAS which at least qualitatively will maximize net social benefits of IAS management. The tool developed here can also be coupled with other impact assessment systems and can thus be versatile and adjustable. The tool has so far been tested on vascular plants only, mainly because the prioritization between the many alien plant species is high on the agenda of the environmental authorities. However, this tool could also quite easily be developed and adapted to other organism groups, as both costs of mitigation and benefits in terms of ecosystem services are general tools and not applicable to plants only.

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Supplementary material I

Table S1

Authors: Rakel Blaalid, Kristin Magnussen, Nina Bruvik Westberg, Ståle Navrud

Data type: table

Explanation note: List over all species included in the analysis with additional risk categories.

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