A practical tool for assessing ecosystem services enhancement and degradation associated with invasive alien species

INvasive Species Effects Assessment Tool (INSEAT)

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Abstract

Current approaches for assessing the effects of invasive alien species (IAS) are biased towards the negative effects of these species, resulting in an incomplete picture of their real effects. This can result in an inefficient IAS management. We address this issue by describing the INvasive Species Effects Assessment Tool (INSEAT) that enables expert elicitation for rapidly assessing the ecological consequences of invasive alien species using the ecosystem services framework. INSEAT scores the ecosystem service “gains and losses” using a scale that accounted for the magnitude and the reversibility of its effects. We tested INSEAT on 18 invasive alien species in Great Britain. Here, we highlighted four case studies: *Harmonia axyridis* (Harlequin ladybird), *Astacus leptodactylus* (Turkish crayfish), *Pacifastacus leniusculus* (Signal crayfish) and *Impatiens glandulifera* (Himalayan balsam).

The results demonstrated that a collation of different experts’ opinions using INSEAT could yield valuable information on the invasive aliens’ ecological and social effects. The users can identify certain invasive alien species as ecosystem services providers and the trade-offs between the ecosystem services provision and loss associated with them. This practical tool can be useful for evidence-based policy and management decisions that consider the potential role of invasive species in delivering human wellbeing.

Keywords

Alternative management; Expert judgement; Great Britain; Non-native; Novel approach.

Introduction

Invasive alien species (IAS) are human-mediated introduced species that sustain self-replacing populations and have the potential to spread over long distances, producing reproductive offspring normally in large numbers (Richardson, Pyšek & Carlton, 2011). These aliens are considered a threat to human health and economy (Simberloff, 2000), as well as one of the main causes of native species extinction (Wittenberg & Cock, 2001; Brennan & Withgott, 2004; Convention on Biological Diversity, 2008). Many have, however, questioned the direct causality between IAS dominance and native species decline in degraded systems (Slobodkin, 2001; Gurevitch & Padilla, 2004; Didham et al., 2005; Schlaepfer, Sax & Olden, 2012): some IAS are perceived as "passengers", rather than the "drivers", of the ecological change primarily caused by habitat modification (Byers, 2002; Seabloom, Harpole, Reichman & Tilman, 2003; Corbin & D'Antonio, 2004; MacDougall & Turkington, 2005). Furthermore, our understanding of the socio-economic and environmental effects of IAS could potentially be biased as a result of over-reporting of their negative effects (Levine et al., 2003; McMahon, Fukami & Cadotte, 2006; Davis, 2009; Schlaepfer, Sax & Olden, 2011; Schlaepfer, Sax & Olden, 2012; Bonanno, 2016). In fact, there are relatively few empirical studies that present information about the benefits provided by IAS, although the focus on this literature has been increasing in the last years (Shackleton et al., 2007; Kull et al., 2011; Tassin & Kull, 2015). The so-called "conflict species" can be highly regarded for the benefits they provide. But they can also be considered as a serious environmental threat from a management perspective.

Many risk and impact assessments have been developed to prioritize IAS control and management, with a focus on the negative environmental impacts and economic damages

(Roy et al., 2014). Prevention has been increasingly recognised as the most cost-effective strategy to ensure pristine ecosystems remaining free of IAS (Meyerson & Mooney, 2007; Genovesi & Monaco, 2013), even though it is not foolproof (Chornesky et al., 2005). IAS control and eradication are often advocated as consequent management operations and require huge financial resources (Ewel & Putz, 2004; Boonman-Berson, Turnhout & van Tatenhove, 2014). Yet, high rates of species invasions are projected to increase in the future. Suggestions have been proposed towards building or maintaining ecosystem resilience and services, rather than restoring IAS-free ecosystems that may be futile (Pyšek & Richardson, 2010; Lin & Petersen, 2013). Although this approach is controversial due to the importance of the evolutionary context in species interactions (Richardson & Ricciardi, 2013) and the unpredictability of some negative consequences of invasions, there is nevertheless a pragmatic need for management alternatives to IAS removal (McMahon, Fukami & Cadotte, 2006; Hulme, Pyšek, Nentwig & Vilà, 2009).

Ecosystem services (ES) are the processes, functions or ecological characteristics through which ecosystems sustain and fulfil human life, either *directly* (e.g. provision of food) or *indirectly* (e.g. pollination) (Daily, 1997; Costanza et al., 2017). IAS may cause changes in these services by altering the ecosystems (Vilà et al., 2010; Peh et al., 2015; Vilà & Hulme, 2017). Therefore tools, such as risk-assessment schemes, that help to evaluate such impacts and aid for the prioritization and management of IAS are essential. Roy et al., (2018) identified 14 minimum attributes a risk-assessment scheme should include, of which two are related to human well-being: 'Assessment of impact on ecosystem services' and 'Assessment of socio-economic impacts'. These attributes were also two of the most notable gaps in our knowledge required for completing risk assessments.

However, IAS ES impact assessments are always challenging and require substantial resources for three reasons: first, ecosystem services are governed by complex interactions that make them difficult to measure over space and time; second, long-term, large-scale data often do not exist (Kremen, 2005; Eviner, Garbach, Baty & Hoskinson, 2012); and last, current measures of many ES are still crude (Naidoo et al., 2008; Bennett, Peterson & Gordon, 2009). Yet, new standards to evaluate IAS effects on human well-being have been developed (Pejchar & Mooney, 2009; Çinar, Arianoutsou, Zenetos & Golani, 2014; Dickie et al., 2014; McLaughlan, Gallardo & Aldridge, 2014). An important example is the Socio-Economic Impact Classification of Alien Taxa (SEICAT; Bacher et al. 2018) that evaluates the impacts on human welfares using changes in human activities as metric; a sister-scheme of the Environmental Impact Classification of Alien Taxa (EICAT) which is officially adopted by IUCN. This scheme has been formulated under the assumption that IAS are drivers of the change, and purposely do not consider their positive impacts.

Here we describe the INvasive Species Effects Assessment Tool (INSEAT), a new approach that contributes to the current scenario of IAS assessment in several aspects. INSEAT significantly differs from previous attempts as it considers both positive and negative impacts of IAS on ES, with the objective to obtain a fair and informed evaluation. INSEAT uses the ES framework, commonly classified into provisioning, regulating and cultural services. This differs from SEICAT which uses the constituents of human well-being; and EICAT, which defines its own categories of environmental impacts. The employment of the ES framework in INSEAT would aid the interpretation of the results, as it is a well-known concept widely accepted by the conservation practitioners. Furthermore, INSEAT can provide insights on knowledge gaps within the expert community.

This practical tool, however, would not yet address complexities such as discerning effects that are temporally or spatially scale-dependent, or accounting for biological factors such as lag-times, dispersal, interactive effects and environmental context. Nevertheless, INSEAT can yield valuable information for IAS managers by enabling them to (1) evaluate rapidly experts' opinions on how IAS affects ES delivery, including positive IAS effects; (2) gather knowledge and information to enable exploration of alternative management options; (3) produce simple, graphical representation of synergies and trade-offs among the effects of IAS; and (4) assess the management effort required to eradicate an alien species. This would make IAS management more efficient and diverse, in terms of exploring management potential that is overlooked under current methodologies. Information obtained by using INSEAT can then be fed into an integrated approach which, amongst other activities, involves seeking stakeholder opinions on the way forward (Cook & Proctor, 2007; Liu, Proctor & Cook, 2010).

In this study, we piloted INSEAT to assess the effects of 18 well-known IAS in Great Britain (GB) on ecosystem service provision. However, due to space constraint, we described only four case studies here: *Harmonia axyridis* (Harlequin ladybird), *Astacus leptodactylus* (Turkish crayfish), *Pacifastacus leniusculus* (Signal crayfish) and *Impatiens glandulifera* (Himalayan balsam). The feedback from the experts then led to a further refinement of the tool which includes an improved impact scale definition; an assessment of uncertainty on the experts' responses; and a request of supporting information from the experts.

Methods

A concise, yet informative, ES classification scheme is essential for IAS managers to understand the different types of ES. We built an integrated ES classification scheme

(Appendix 1) based on three widely-accepted ES classifications from the Millennium Ecosystem Assessment (MA, 2005), the UK National Ecosystem Assessment (UK NEA; Mace et al., 2011) and The Economics of Ecosystem and Biodiversity (TEEB, 2016). We excluded supporting services in our ES classification scheme to avoid double-counting since all the other services are underpinned by them (Haines-Young & Potschin, 2012).

Assessing IAS effects on ES requires a qualitative and broad evaluation (Roy et al., 2014). INSEAT is designed to be completed by experts on a particular IAS by scoring its effect on a range of ES from our ES classification scheme (although other ES classifications could also be used). We created an integrated assessment proforma (Fig. 1) that included questions designed to assess (1) the strength and direction of IAS effects on ES provision; (2) IAS potential to provide ES; and (3) the management effort required to eradicate the alien species.

Using experts' opinions

The INSEAT protocol relies on expert judgement, which is often sought when there is scientific uncertainty or when data are absent or insufficient (Hemming et al., 2018). However, experts' reliability can be compromised, as experts are prone to biases and heuristics. Hence, numerous expert elicitation techniques have been developed (Sutherland & Burgman, 2015; O'Hagan et al., 2006; Cooke, 1991). In general, experts must be tested with their estimates validated with independent evidence, in order to improve their accuracy; and independent opinions should be sought. However, expert elicitation remains largely informal and non-transparent. To improve the accuracy of expert judgement as well as the transparency of the results, Hemming el al. (2018) published a structured elicitation protocol called IDEA (Investigate, Discuss, Estimate and Aggregate). This protocol allows the experts to answer the questionnaire individually while providing reasons for their judgements; and modify their responses discreetly after reviewing the answers from other anonymous respondents.

INSEAT, however, does not follow all the steps prescribed by IDEA as it does not seek to establish a definite rational consensus on IAS management. Instead, it is designed as a rapid screening tool for assessing the divergences in the opinions from a large number of IAS experts. INSEAT allows gathering of information about the sources of knowledge that these experts used (see Question 6 in Fig. 1), so that the users can critically review their responses. The tool also seeks to open debate on alternative management options, which can be achieved only if a large number of experts complete the survey. By having short response times, INSEAT has the possibility to gather a high amount of responses.

A number of measures have been taken to minimise bias and improve the level of confidence: First, INSEAT stresses that the respondent should be an expert in the IAS of interest. Second, the respondents should be selected carefully – for example, we focused only on the IAS experts from Great Britain when piloting the tool, since IAS effects are mostly context dependent (Pyšek & Richardson, 2010; Vilà et al., 2011). Third, the language used in the questionnaire has been tested during the pilot phase and improved, to avoid language-based uncertainties. Fourth, the experts are asked to gauge their level of confidence in their responses (this was added on to the final version of INSEAT after piloting). Finally, the experts are asked to provide evidence to support their answers in order to weight their opinions (this was added on to the final version of INSEAT after piloting).

Assessing strength and direction of IAS effects

Semi-quantitative Likert scales are used to rank environmental and socio-economic impacts, following other assessments such as the Generic Impact Scoring System (GISS; Nentwig et al., 2016). Each scale level is well-defined to avoid ambiguities and also to make categories and taxa comparable. The scale ranges from -4 to 4, each level combining the *strength* ("no effect", "too small", "noticeable", "substantial" and "intense") and the *reversibility* of the impact if the species is removed ("reversible" or "irreversible"). We consider that only "intense" effects can be irreversible, as for less extreme impacts the ecosystems would naturally recover to their original state.

We used the variability of agreement among the respondents as a measure of robustness in the knowledge of a species in terms of its impact on a particular ES. Low agreement, inferred by a high variability in the scoring, helps to identify knowledge gaps about the effect of that species.

We assumed that the effect of a widely-distributed species to be greater than if it were more narrowly distributed. Therefore, the "Impact Index", was determined by weighing the *species impact* (from -4 to 4) score with its *spatial occupation* score (from 1 to 3) (i.e. *Impact index=impact*occupation*). The spatial occupation score of the invasive species in their non-native range– ranging from 1 (localized occupation) to 3 (nationwide occupation) – was obtained from the respondents. Hence, *Impact index* scores range from -12 to 12: scores from -12 to -4 indicate strong negative impacts, scores from -4 to 4 indicate mild or null effects and scores from 4 to 12 indicate strong positive effects. The colour code on the "Index graphs" (Figs 1.b, 2.b and 3.b) is based on this division: dark grey denotes strong negative effect; light grey denotes mild effect; and white denotes strong positive effect.

Finally, we wanted to know the similarities and contrasts in the effects among species. This might be useful to answer ecological questions – such as '*Do IAS from same taxonomic groups have similar effects, and do those effects differ between taxonomic groups?'* – that may ultimately help to design management plans. Then we used k-means clustering algorithm (Hartigan & Wong, 1979) to determine the naturally occurring groups within the dataset, and the Silhouette Plot method (Appendix 3) to measure the fitness of the clustering (Kaufman & Rousseeuw, 2009).

Assessing species potential to provide ES

We assumed that IAS have a potential to provide ecological or cultural benefits under appropriate management (defined as any management scenario that would lead to the improvement of a particular ecosystem service provided by a species). To assess this, the respondents were asked to select a list of ES that could potentially be enhanced by the species in question under adequate management.

Assessing species manageability

Prioritization of cost-effective IAS management is often essential for site managers, due to limited resources. Risk management is a tool for prioritisation of IAS, used together with risk assessment. A risk management scheme, developed by Booy et al. (2017), uses seven key criteria: Effectiveness, Practicality, Cost, Impact, Acceptability, Opportunity window and Likelihood of re-invasion.

As part of the quick IAS assessment proposed here, we developed a basic manageability assessment for assessing the feasibility of eradicating an IAS. This complements the results of the IAS effects assessment by providing a more comprehensive information about the ecology of the species in question. We based the manageability of the species on their *spreading capacity* (i.e., invasiveness), and the *management effort* (i.e., practicality – e.g., physical access and resources such as overall costs, dependent on machinery, staff and materials such as pesticides) that would be required for its eradication locally (see Booy et al., 2017).

Two semi-quantitative Likert scale questions were included in the survey to obtain scores for the spreading capacity and the required management effort, respectively (Fig.1, questions 2 and 3). The scores are then presented in a scatter plot to represent the manageability of the species (Fig. 6). Species on the top left corner require more resources to be eradicated than species on the bottom right corner.

Piloting INSEAT: case studies

Approximately 3,864 alien species are currently established in Great Britain (Zieritz et al., 2014). However, only 15.3% of them are considered to have negative effects on the environment or human wellbeing (Roy et al., 2012). For piloting INSEAT, we selected eighteen most-studied IAS from six taxonomic groups – namely, terrestrial higher plants, mammals, aquatic crustaceans, birds, insects and marine plants – to allow comparisons within and between groups (Appendix 4).

The respondents selected for piloting INSEAT were all IAS experts in Great Britain. We identified these respondents from the Delivering Alien Invasive Species Inventories for Europe (DAISIE) database, as well as the relevant scientific publications. We contacted a total of 452 experts via email, requesting them to complete an anonymous online survey (https://www.isurvey.soton.ac.uk/) on a voluntary basis. This pilot exercise was approved by an Ethics Committee at the University of Southampton.

All the graphical outputs and statistical analysis were performed using RStudio 3.3.1 (R Core Team, 2016), R packages "ggplot2" (Wickham, 2009), "ggrepel" (Slowikowski, 2016) and "Flexible Procedures for Clustering" (Hennig, 2015). The pilot assessment form can be found in Appendix 2; this assessment form improved after the pilot thanks to the feedback provided by the respondents and reviewers. The final assessment form is shown in Fig. 1.

Categorising level of confidence

We acknowledge the feedback from the testing of INSEAT that the pilot proforma lacks the capacity for the experts to validate their responses. The fact that respondents did not need to justify their answers or indicate their degree of uncertainty may strongly reduce the reliability of the assessment. Although the strength of INSEAT lies on its ability to rapidly obtain responses from a large number of experts, scores derived from this tool will inevitably have varying degree of uncertainty associated with them. In order to keep a balance between practicality and reliability, we added a section in the revised proforma asking the respondents to report the confidence level of their assessment for each ES (as High, Medium or Low; for definitions, see Fig. 1). We also added a request to the respondents for information (e.g. scientific evidence, personal observations, professional opinions) that support their scores in general. Understanding the uncertainty of the responses and its implications can help to further inform IAS management decisions.

Results

Our pilot survey, covering 18 IAS, was completed by 78 IAS experts in total (i.e., response rate of 17%). The average number of species completed by a respondent was 3 (95% CI = 0.41) and the average time to complete the questionnaire (the pilot version) for one species was 8.4 minutes (95% CI = 1.94). Each species was assessed 12.8 times on average (95% CI

=3.84), with marked variations between taxonomic groups: higher plants received a total of 75 completed assessments; mammals 47; aquatic crustaceans 45; birds 28; insects 19; and marine plants 16. The most assessed species were *Fallopia japonica* (Japanese knotweed) with 28 completed assessments, *Impatiens glandulifera* (Himalayan balsam) with 26 and *Sciurus carolinensis* (Grey squirrel) 22. The least assessed were *Frankliniella occidentalis*, (Western flower thrips) with 5 completed assessments, *Codium fragile* (Green sea fingers) 3 and *Leptoglossus occidentalis* (Western conifer seed bug) 2 only (see Supporting Information).

Here we highlight the survey results of four IAS, showcasing how INSEAT can rapidly identify the ecosystem services enhanced or degraded by a particular IAS. The species highlighted here were chosen for their contrasting results, which help to illustrate how INSEAT can highlight variability in agreements among experts (for the results of the rest of the species, see Data accessibility section).

- *Harmonia axyridis* (Fig. 2) - Harlequin ladybird is an Asian beetle, introduced in Europe for pest control that has accidentally arrived in Great Britain crossing the Channel together with imported vegetables. It was first recorded in Essex in 2004. Currently, it is well established in England and Wales while rapidly spreading to Scotland (Roy, 2015). This invasive species was assessed by 12 experts in this study. The experts agreed that *Harmonia axyridis* has a positive impact through its effect on pest regulation. This also has a synergistic association with other benefits such as the production of cultivated goods (Fig. 2.a). Furthermore, 30% of the experts considered that this ladybird is potentially beneficial for provision of fuels (i.e., beneficial for standing vegetation) and harvested wild goods (Fig. 2.b). However, the experts had also identified some negative effects associated with this

IAS; primarily this species could adversely affect wild species diversity, or genetic diversity (with a median score of -2). Therefore, this case study demonstrates how the tool could be employed to detect important trade-offs between the provision and loss of services associated with an invasive species (Fig. 2.c).

- *Astacus leptodactylus* (Fig. 3) - Turkish crayfish occupies lakes, ponds and rivers, but it has also been recorded in brackish water (Aldridge, 2016). This species was first recorded in 1975. Currently, it is well established in England with isolated populations in Wales as well. This invasive species was assessed by 12 experts. The overall effect of this species in the country is considered as "mild" as none of the effect index is higher than 3 or lower than -3 (Fig. 3.c). This case study, however, highlighted a discrepancy among the experts in terms of their views on the usefulness of this species used as a food source (Fig. 3.a). Nevertheless, 50% of the respondents indicated that there is a potential of this species to be used as a harvested wild good (Fig. 3.b).
- *Pacifastacus leniusculus* (Fig. 4) – Interestingly, the experts' opinions on Signal crayfish were greatly different from those of the Turkish crayfish. Hence, this case study serves as an example of how similar species are considered to have vastly different effects by the assessed experts. Assessed by 16 experts, this invasive species had negative impact index scores on wild species diversity (median score = -4), erosion regulation (median score = -3), detoxification (median score = -0.5), hazard regulation (median score = -1), pest regulation (median score = -1), and recreation (median score = -0.5) (Fig. 4.a). Despite the majority of the effects being negative, 70% of the experts indicated that this crayfish could potentially be used as a harvested wild good (Fig. 4.c).

- *Impatiens glandulifera* (Fig. 5) - Himalayan balsam is an annual weed native from the Indian subcontinent. Recorded for the first time in 1851 in Great Britain, it is currently distributed through most lowland. (Day, 2015). We had 26 experts assessing this species. The majority of the effects of this invasive species were considered negative (Fig. 5.a). The level of congruence for two particular ES is low (i.e., high uncertainty): erosion regulation (median score of -3; quartiles ranging from 0 to -4), and pollination, (median score of 1; quartiles ranging from 3 to -3). Nevertheless, the impact index scores clearly indicated that this species as highly damaging to the environment (Fig. 5.c).

Manageability and clustering analysis

Overall, the manageability of all 18 IAS in this study is low, with a *management effort* median score of 3.0 (Median Absolute Deviation = 0), and *spreading capacity* median score of 2.3 (MAD = 0.74). This means that all species in this study would require a high amount of resources for their control. The species with the lowest manageability were (Fig. 6): *Dikerogammarus villosus* (Killer shrimp), *Undaria pinnatifida* (Wakame), *Harmonia axyridis*, *Sargassum muticum* (Wireweed) and *Pacifastacus leniusculus*.

The clustering analysis indicated that the best number of clusters for our species sample is three, with an average silhouette width of 0.27. This silhouette width is substantially low, indicating a weak clustering structure (see Supporting Information). Hence, no statistically significant cluster was found among the 18 IAS in the study (Kaufman & Rousseeuw 2009).

Discussion

Preventing IAS spread is the most cost-effective strategy to build IAS-free ecosystems (Richardon & Ricciardi, 2013). However, such management approach is unlikely to be 100% effective (Chornesky et al., 2005); and the on-going rapid rates of species invasion suggest that eradication of IAS may not be economically feasible in the future. In such scenario, goals of coexistence would be more viable and realistic (Hobbs et al., 2006; Hobbs, Higgs & Harris, 2009; Walther et al., 2009).

By using INSEAT, conservation practitioners and site managers can improve their understanding of the invasive species and their associated ecosystem service gains and losses. Such knowledge based on experts' opinions can potentially aid in the prioritization of IAS management and the consideration of alternative management measures in decision-making. Nevertheless, INSEAT should still be considered as a practical tool for preliminary assessments; the results of INSEAT are based on opinions of single individuals, hence they provide an initial screening of possibilities that should be further evaluated in later stages of decision-making processes. However the use of INSEAT could potentially pave the way for the more detailed evaluation in the future.

INSEAT can highlight the level of confidence in our current knowledge of IAS, thus enabling us to pinpoint any research gaps and/or conjectures, as negative connotations of some alien species may be based on incomplete information (McMahon, Fukami & Cadotte, 2006; Davis, 2009; Schlaepfer, Sax & Olden, 2011; Schlaepfer, Sax & Olden, 2012; Bonanno, 2016). The lack of congruence in the responses from our pilot scheme could be due to the unclear definitions of the impact scales (which we have improved after piloting). Another possible explanation for the low level of congruence in the responses could be the interpretative flexibility of the experts. It is known that opinions among experts about the valuation of IAS effects often diverged (Humair et al. 2014). This is because the notion of IAS as concepts have similar but not identical meaning to different group of experts and stakeholders; this interpretative flexibility bears the risk of introducing misunderstandings. Humair et al.

(2014) urged IAS experts to acknowledge uncertainties, to engage transparently in deliberation about conflicting issues and to take the role of impartial mediators of policy alternatives rather than of issue advocates. INSEAT supports this observation, with an aspiration that our results will aid in this deliberation.

In some IAS, the direction of their effects on certain ES remained equivocal. For instance, the impact score of Himalayan balsam on pollination ranged from 3 to -3. Furthermore, the socio-cultural attitudes of the respondents towards a particular species could also vary. This was prominently reflected by the significant variations (ranging from positive to negative) in the impact scores for cultural ecosystem services – such as “aesthetics” – in many cases. As the assessments on cultural services are dependent on personal views, it could therefore inevitably be opened to more ambiguous outcomes.

Having incorporated the positive effects provided by IAS, INSEAT provides a more comprehensive assessment of the IAS consequences across different types of ES, as opposed to focusing on the negative aspects exclusively. This will provide users new insights into the species, allowing diversification of management actions. Once the prevention measures have failed, goals of coexistence are more feasible than eradication in terms of economic resources, time and management effort (Wittenberg & Cock, 2005; Davis, 2009). Hence, these management strategies should be preferred whenever it is possible. Successful management strategies often acknowledge “that the primary and inevitable constant of the natural world is change” (Davis, 2009). Therefore, we suggest an adaptive management approach to deal with IAS (Murray & Marmorek, 2003) in which INSEAT would allow users to: (1) synthesize the experts’ opinions of IAS effects; (2) collect the information that support such opinions; and (3) explore management actions alternative to control and eradication. A re-evaluation of known effects in the context of ES can help to bridge the link between IAS and human wellbeing (Millennium Ecosystem Assessment, 2005). There are accounts of how the removal of an alien species could compromise the provision of cultural ecosystem services in a local context and lead to strong public opposition (Dickie et al., 2014; Bennett, 2016; Bonanno, 2016). Information gathered about the effects of an invasive species can be used, in combination with local knowledge, to work with stakeholders to identify the most appropriate management plan. For example, *Sciurus carolinensis* (grey squirrel) – one of the pilot species in this study – had received positive impact scores on multiple cultural ES and comments such as "*for some people in the most urbanized areas, grey squirrels are their only experience of wildlife*". The removal of grey squirrel had led to strong public opposition in the past (Bremner & Park, 2007); INSEAT would have allowed wildlife managers to circumvent public outrage by identifying alternative, socially-acceptable squirrel management plans.

One useful feature of INSEAT is that it could highlight the potential benefits that an invasive species could provide under appropriate management (Figs. 1.b, 2.b, 3.b, 4.b). Under certain climate change scenarios, some non-native species have even been considered necessary to assure local ecosystem function continuity (Walther et al., 2009; Lin & Petersen, 2013). Cases of IAS providing refuge for native species have also been reported (Chiba, 2010). We therefore argue that consideration of management alternatives to the *status quo* can help to mitigate negative impacts while taking advantage of the alien species; IAS can be a valuable resource in their own right, and management actions that take advantage of their potential benefits could be fruitful. A comment from an expert on *Cervus nippon* (Sika deer) supported our case: "*if deer numbers could be controlled, perhaps by bringing back the Lynx, there are definitely positive benefits*". Another example that justified the usefulness of IAS is that both Turkish and Signal crayfish scored high in their potential as wild food resource, with 50% and 70% of experts in agreement, respectively. Management measures that include harvesting of wild populations could decrease their numbers, diminish their negative effect on other services and increase the cultural values that are associated with the harvest. However, when such management is considered, it should be done with precaution: many examples in the literature illustrate the risk of exploiting invasive species e.g. promoting the intentional introduction of fish and crayfish into areas where the species was not present (McLaughlan & Aldridge, 2013; McLaughlan, Gallardo & Aldridge, 2014). In such cases, site managers could explore if recreational harvest accompanied with IAS awareness and education is a possible solution for preventing unintended consequences of exploiting invasive species.

IAS management involves an estimation of the resources required for effective control. INSEAT allows users to visualise the level of manageability of an invasive species (Fig. 6), thus providing a preliminary assessment of feasibility of IAS management. To enhance the efficacy of a control measure, the tool also allows users to distinguish groups of IAS with similar effects. Our clusters were not statistically significant for all pilot species; this is not surprising given that they were from six different taxonomic groups. To be useful, the clustering analysis should include invasive species from the same taxon (e.g. avian) only.

Finally, we believe that INSEAT can be applied on a user-friendly web interface and adapted as an online survey which can be completed rapidly. It can be adapted to different geographical or political regions; and the results are visually informative and self-explanatory for site managers and stakeholders.

Limitations and future perspectives

INSEAT – as a rapid assessment tool – inevitably has limitations. It does not deal with complex ecological interactions, scale-dependent effects, intricate ecological context, and spread mechanisms. INSEAT could not provide answers to the many complexities in ecosystem services science. For example, it is beyond the scope of the tool to address sustainability and resilience of the ecosystem services associated with IAS. Nevertheless, INSEAT should complement other risk assessments (e.g. Booy et al., 2017) and be used to build awareness, detect knowledge gaps and aid in the design of alternative management strategies. In fact, a bridge between INSEAT and EICAT, which evaluates, compares, and predicts the magnitudes of the environmental impacts of different IAS taxa (Hawkins et al., 2015), would be beneficial for both IAS management and policy. Decision makers could then evaluate all the knowledge available, while exploring management alternatives, by focusing on the functional role rather than on the origin of the species (Bonanno, 2016).

Authors' contributions

R.M.-C. and K.S.-H.P. conceived the ideas; R.M.-C. and K.S.-H.P. designed the tool with the input from E.J., S.W. and P.V.; R.M.-C. collected the data; R.M.-C. and A.P.-D. analysed the data; and R.M.-C. wrote the manuscript, with all co-authors contributing to the earlier drafts

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Data accessibility

Data generated by INSEAT for the case studies will be available through DRYAD, and include the following: (1) the raw data, consisting on the online surveys as downloaded from https://www.isurvey.soton.ac.uk, (2) the data file used to analyse the results, obtained by cleaning the raw data file and (3) R files required to build the graphical outputs designed for INSEAT. For each species, the graphical outputs generated (impact scores, potential and impact index graphs) will be shared through FIGSHARE.

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Figure legends

Figure 1. INvasive Species Effects Assessment Tool (INSEAT). Assessment form - questions and scoring system (final version). The pilot assessment form, as well as the changes implemented after respondents and reviewers' feedback, can be found in Appendix 2.

Figure 2. *Harmonia axyridis* (Harlequin ladybird). N=12. The horizontal axis displays the ES grouped into broader categories. a) Impact scores. Boxplot indicates the interquartile range; the band represents the median. b) Potential. Percentage of the respondents that considered that an ES could be potentially provided by the species. c) Impact index. White indicates strong positive impact; dark grey represents strong negative impact. Note: these results are based on the INSEAT pilot assessment form (Appendix 2).

Figure 3. *Astacus leptodactylus* (Turkish crayfish). N=12. The horizontal axis displays the ES grouped into broader categories. a) Impact scores. Boxplot indicates the interquartile range; the band represents the median. b) Potential. Percentage of the respondents that considered that an ES could be potentially provided by the species. c) Impact index. Light grey indicates strong positive impact; dark grey represents strong negative impact. Note: these results are based on the INSEAT pilot assessment form (Appendix 2).

Figure 4. *Pacifastacus leniusculus* (Signal crayfish). N=16. The horizontal axis displays the ES grouped into broader categories. a) Impact scores. Boxplot indicates the interquartile range; the band represents the median. b) Potential. Percentage of the respondents that considered that an ES could be potentially provided by the species. c) Impact index. Light grey indicates strong positive impact; dark grey represents strong negative impact. Note: these results are based on the INSEAT pilot assessment form (Appendix 2).

Figure 5. *Impatiens glandulifera* (Himalayan balsam). N=26. The horizontal axis displays the ES grouped into broader categories. a) Impact scores. Boxplot indicates the interquartile range and the band represents the median. b) Potential. Percentage of the respondents that considered that an ES could be potentially provided by the species. c) Impact index. Light grey indicates strong positive impact; dark grey represents strong negative impact. Note: these results are based on the INSEAT pilot assessment form (Appendix 2).

Figure 6. Scatter plot representing the manageability of the species. X-axis represents the median of the spreading capacity; y-axis represents the median of the management effort. Species in the top, right corner are the species with the lowest manageability. Note: these results are based on the INSEAT pilot assessment form (Appendix 2); the final version includes an improved definition of the management effort (Fig. 1).