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ORIGINAL PAPER

A modular assessment tool for managing introduced fishes according to risks of species and their populations, and impacts of management actions

J. Robert Britton · Gordon H. Copp · Matt Brazier · Gareth D. Davies

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Abstract A modular assessment scheme for assisting the risk management of introduced fishes is described, with its recent application to England and Wales demonstrated. The initial module prioritises the introduced fishes in the risk assessment area according to their potential invasiveness and current distribution. The second module then assesses populations of the prioritised species in relation to the character of their receiving waters and the potential risks posed by their population in that circumstance; the output is a suggested management action for each population. The third module evaluates the suggested management action in relation to its potential impacts in the environment and how these impacts may be mitigated. The final module assesses the estimated cumulative cost of the selected management action relative to an alternative action. To demonstrate its potential value for managing extant populations of introduced fish, three eradication case-studies from England were assessed retrospectively using the scheme. This revealed eradication of two topmouth gudgeon *Pseudorasbora parva* populations was commensurate with their levels of ecological risk in the environment. By contrast, initial assessment of the eradication of a feral population of fathead minnow *Pimephales promelas* suggested control and containment was the commensurate management action due to a relatively low risk of natural dispersal. Application of the scheme elsewhere in the world and to other faunal groups should enable more objective decision-making in management programmes and enhance conservation outcomes.

Keywords Decision support · Alien · Introductions · Invasive · Risk management

J. R. Britton (✉) · G. H. Copp · G. D. Davies
Centre for Conservation Ecology and Environmental Science, School of Applied Sciences, Bournemouth University, Poole, Dorset BH12 5BB, UK
e-mail: Rbritton@bournemouth.ac.uk

G. H. Copp
Salmon and Freshwater Team, Centre for Environment, Fisheries and Aquaculture Science, Pakefield Road, Lowestoft NR33 0HT, UK

M. Brazier
North Area North West Region, Environment Agency, Penrith, Cumbria, UK

G. D. Davies
Fisheries Technical Services, Environment Agency, Bromholme Lane, Brampton, Huntingdon, Cambridgeshire PE28 4NE, UK

Introduction

Changes in the global environment as a result of human activity have increased dramatically in the last 100 years (Pimm et al. 1995), with human-mediated introductions of non-native species being one of the most widespread and potentially damaging of these pressures (Sala et al. 2000). Some introduced species have minimal impacts on their receiving ecosystem, whereas others have been observed to exert detrimental effects such as alterations to community structure and ecosystem function (Sala et al. 2000). In cases where efforts fail to prevent a species' introduction, current evidence suggests that the impacts by potentially invasive species can be inhibited or eliminated through appropriate management programmes that impede establishment and/or reduce the potential risks of wider dispersal (Simberloff 2009; Britton et al. 2010a). However, few countries routinely incorporate such management programmes into their regulation of introduced species (Copp et al. 2005a; Nuñez and Pauchard 2010; Britton et al. 2011), with rapid response strategies and infrastructures only now starting to be developed (Britton and Brazier 2006, Britton et al. 2010a; Thomas 2010).

Eradication remains an important tool in managing the distribution of introduced species, and there have been numerous successful eradications of faunal groups from large spatial areas. Although continental-wide eradications remain scarce, there have been over 700 successful species eradications from islands, including 332 successful operations on rodents (Howald et al. 2007). Moreover, Simberloff (2009) provided many examples of successful eradications of plants, insects, mammals and algae. Management actions that have successfully targeted the eradication of introduced fishes over large spatial areas are less common (Britton et al. 2011). Where eradication has been used successfully against introduced fish, it has generally been on small, enclosed water bodies either as independent actions (Wheeler 1998; Copp et al. 2007a) or part of a larger control programme (Britton et al. 2010a). This suggests that the ability to manage introduced fish in the environment is challenging and either rarely completed or not reported (Britton et al. 2011). Indeed, in a recent paper on managing introduced species in the European Union, fish were not even mentioned (Hulme et al. 2009). Yet the success of eradicating species from islands suggests that there is scope for managing introduced fish at the river basin or catchment level, which effectively represent "biogeographic islands" that provide a closed management area for actions to be implemented (Leprieur et al. 2009; Saunders et al. 2010; Britton et al. 2011).

Irrespective of the spatial scale at which the management action is taken, it must be commensurate with the risks posed by both the target species in the environment and the potential indirect consequences of that action. For example, no risk analysis was undertaken in the Netherlands to assess the potential impacts of pond management actions to remove organic matter and macrophytes that have indirectly and unexpectedly enhanced these pond habitats for non-native pumpkinseed *Lepomis gibbosus* (van Kleef et al. 2008). Therefore, the management of introduced species should consider all possible foreseen risks associated with the target species as well as those of the potential management actions that may be employed against them. This process of assessing the potential impacts of species and their management actions can be enhanced through the use of analytical tools based on risk analysis and risk management (e.g. Copp et al. 2009; Britton et al. 2010a). Environmental risk analysis comprises the identification, assessment and management of environmental hazards, with risk management consisting of the identification, evaluation, selection and implementation of appropriate management actions to reduce the risks of the identified hazards (Andersen et al. 2004; Copp et al. 2005a; Britton et al. 2011). Thus, environmental management programmes that are underpinned by decision-support tools founded on risk analysis and risk management should aim to identify priority species and then their populations that require management interventions (Britton et al. 2010a).

The aim of the present paper is to describe a modular scheme recently developed in England and Wales that prioritises introduced fishes by risk and then assesses the potential impacts of management options and their impacts for the control and/or eradication of the target populations. To demonstrate the scheme's application to real-world situations and its wider applicability to areas outside of England and Wales, it has been applied retrospectively to three case-studies to identify the management actions that would have been commensurate with the relative risks posed by the species concerned within a local and national context.

Methodology

This assessment scheme consists of four modules: 1) Prioritisation of introduced fish; 2) Species risk to the receiving water and catchment; 3) Impact of the

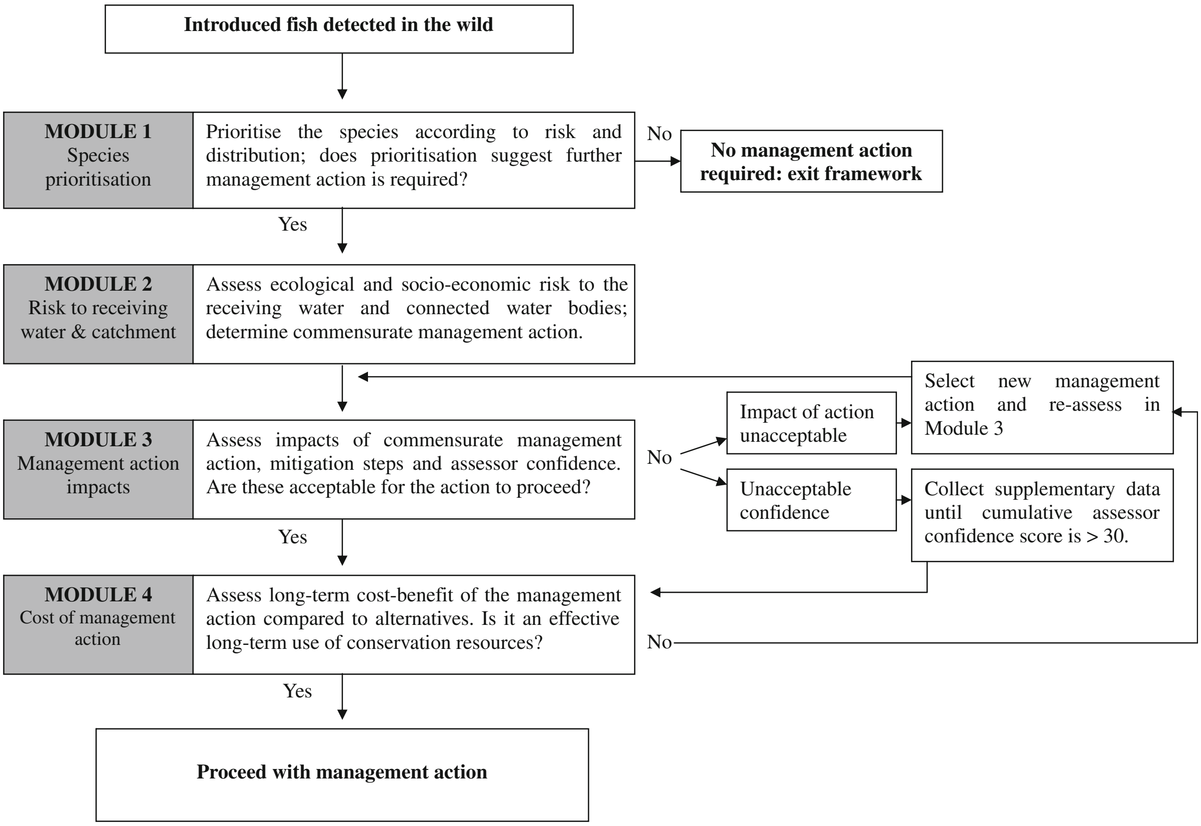

Fig. 1 Flow chart demonstrating the use of the developed modular assessment tool for managing introduced fishes according to risks of species and their populations, and impacts of management actions, following the detection of an introduced fish in the wild

management action; and 4) Cost of the management action. These are discussed in turn. A flow chart is provided in Fig. 1 that demonstrates how it may be used following the detection of an introduced fish in the wild.

Module 1: prioritisation of introduced fish in England and Wales

In the prioritisation of non-native species for regulation and control, the use of 'black' and 'white' lists have been employed to classify species according to their perceived higher and lower risk of causing subsequent ecological damage (Simberloff 2006). White-listed species tend to be permitted (or tolerated) for importation and/or introduction to obtain their range of economic and social benefits whilst posing minimal risk to the environment (Simberloff 2006; Gozlan 2008). These lists are often compiled using risk pre-screening tools, which categorise species according to their likelihood of becoming invasive. For example, the Fish Invasiveness Scoring Kit (FISK) was adapted from the Weed Risk Assessment tool (Pheloung et al. 1999) for assessing the potential invasiveness of existing and potential future non-native freshwater fishes (Copp et al. 2005b, c). This pre-screening assessment tool uses a scoring system to assess non-native fishes on a scoring system based on the basis of their 1) biogeography and history; and 2) biology and ecology (Copp et al. 2005b). Higher FISK scores indicate an increased risk of the species being invasive following an introduction (Copp et al. 2005c), and calibration has revealed fishes with scores $\geq$19 to be those that pose the greatest risk (Copp et al. 2009). Although these risk hazard identification tools are generally used to pre-screen fish species either proposed for introduction or likely to be introduced despite the imposition of controls (Copp et al. 2005b;

Branquart 2007; Mastitsky et al. 2010), they can also be used or incorporated into post-introduction assessments (e.g. Copp et al. 2009). In addition to considering the potential invasiveness of an introduced fish, it is also important to consider their current distribution (e.g. Copp et al. 2007b). The successful management of introduced species is heavily reliant on their detection early in their invasion pathway when their populations are still relatively easy to control (Kolar and Lodge 2001). Consequently, when species have already gained a wide spatial distribution, then the ability of management actions to prevent further dispersal is constrained, and it is arguable whether further resources should be expended on controlling these populations, irrespective of any detrimental impacts they may incite.

The purpose of Module 1 is, therefore, to categorise introduced fishes according to their potential invasiveness (e.g. FISK) and known current distribution (e.g. number of sites where present, number of river catchments invaded, length of river invaded). Prompt action is need for species assessed as 'high risk' but currently of limited spatial distribution (i.e. 'black-listed') in order to prevent or inhibit the establishment of invasive populations. Similarly, for high-risk species that have established populations in only a few locations but over a wide area (e.g. topmouth gudgeon *Pseudorabora parva* in the UK; Britton et al. 2008), eradication may provide be an effective means of halting or limiting their further dispersal (e.g. Britton et al. 2010a). Species of medium or high invasiveness risk and whose distribution is rapidly expanding are those for which management decisions are more difficult. With species that are present at numerous locations over a wide distribution area then it is debatable whether eradication operations will impact significantly on their further spread and polices of control and containment may be more effective. Species of low or negligible invasiveness risk should not be considered for further management action and can effectively be considered as 'white-list' species irrespective of their distribution.

In England and Wales, there are at least 28 non-native fishes present either in open waters, listed on non-native fish legislation (Copp et al. 2007b) or are likely to be introduced in the future (Hickley and Chare 2004; Britton et al. 2010b; Fig. 2). Using their calculated FISK scores (Copp et al. 2009; Britton et al. 2010b) in conjunction with their known distribution (number of sites where they have been recorded), they have been grouped into a matrix of 16 risk categories with which to propose broad management recommendations for each species (Table 1; Fig. 2). In conjunction with the FISK calibration and species scores (Copp et al. 2009; Britton et al. 2010b), species with scores >19 have been categorised further to enable additional risk classification

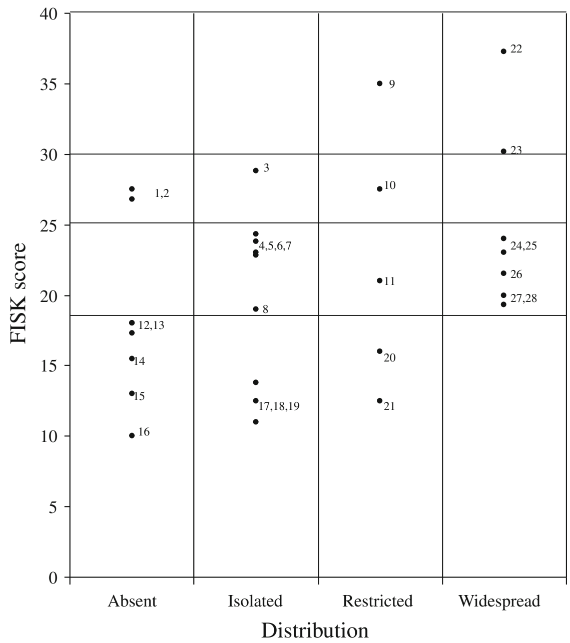

Fig. 2 FISK rating (*cf.* Table 1) and distribution of introduced fishes in England and Wales, where: absent (not present); isolated (1–10 locations); restricted range (11–50 locations); and widespread (>50 locations). Refer to Table 1 for recommended management actions. Species key: *1* American lake charr *Salvelinus namaycush*; *2* giant snakehead *Channa micropeltes*; *3* black bullhead *Ameiurus melas*; *4* bighead carp *Hypophthalmichthys nobilis*; *5* channel catfish *Ictalurus punctatus*; *6* white sucker *Catostomus commersonii*; *7* silver carp *Hypophthalmichthys molitrix*; *8* fathead minnow *Pimephales promelas*; *9* topmouth gudgeon *Pseudorasbora parva*; *10* pumpkinseed *Lepomis gibbosus*; *11* sunbleak *Leucaspius delineatus*; *12* Siberian sturgeon *Acipenser baerii*; *13* red shiner *Cyprinella lutrensis*; *14* largemouth bass *Micropterus salmoides*; *15* rock bass *Ambloplites rupestris*; *16* landlocked salmon *Salmo salar sebago*; *17* brook trout *Salvelinus fontinalis*; *18* European weatherfish *Misgurnus fossilis*; *19* European mudminnow *Umbra krameri*; *20* sterlet *Acipenser ruthenus*; *21* bitterling *Rhodeus amarus*; *22* common carp *Cyprinus carpio*; *23* goldfish *Carassius auratus*; *24* grass carp *Ctenopharyngodon idella*; *25* pikeperch *Sander lucioperca*; *26* European catfish *Silurus glanis*; *27* ide *Leuciscus idus*; *28* rainbow trout *Oncorhynchus mykiss*

Table 1 Recommended management action categories (A–D) for introduced fishes (numbers of species per category given in parenthesis, *cf*. Fig. 2) in England and Wales according to their FISK risk category (see Copp et al. 2009) and current known distribution (i.e. number of sites)

Distribution:	FISK risk category			
	1 (<19.0)	2 (19.0–25.0)	3 (25.1–30.0)	4 (>30.1)
Absent (0)	A (5)	C (0)	C (2)	C (0)
Isolated (1–10 sites)	A (3)	B (5)	B (1)	D (0)
Restricted (11–50 sites)	A (2)	B (1)	B (1)	D (1)
Widespread (>50 sites)	A (0)	B (5)	B (0)	B (2)

A: low priority species: no management action necessary; B: medium priority species: management actions desired; assess feasibility of management options; C: high priority species: implement immediate management action on first detection; D: high priority species: immediate implementation of management actions

(Fig. 2; Table 1). Consequently, the species that pose the highest invasive risk in England and Wales are those with FISK scores >30.1 (Fig. 2; Table 1). This categorisation enables a greater degree of species prioritisation according to their invasiveness; where this scheme is implemented elsewhere, it is recommended that FISK calibration is repeated for the region and species concerned (Copp et al. 2009; Mastitsky et al. 2010).

Module 2: species risk to the receiving water and catchment

For introduced fishes where Module 1 suggests management actions are necessary, Module 2 enables the commensurate management action to be determined for their populations in accordance with the characteristics of both the infested water (where the species is present) and the receiving catchment (where the species might disperse). Using a similar approach to that described by Britton et al. (2010a), the module assesses the risk posed by the introduced species to the infested water and receiving catchment according to a broad series of criteria. These are the: 1) output of Module 1; 2) potential for the species to disperse from the infested water into the receiving catchment; 3) ecological and conservation status of the infested water and receiving catchment; and 4)

Table 2 Criteria and risk categories for water bodies containing populations of introduced fish used in Module 2

Criterion	High risk (3)	Medium risk (2)	Low risk (1)
Relative risk ranking of the non-native fish	High or medium risk species that was previously absent or has isolated populations	High or medium risk species that is restricted in distribution	Low risk species of limited to widespread distribution
Potential for species natural dispersal	Water is located in the flood plain	Water has a direct connection to a river catchment	Lake is fully enclosed with no opportunity for natural dispersal
Ecological and conservation status of infested water	Near-natural ecosystem; endangered species are present	Naturally functioning ecosystem; legally protected species present	Highly degraded ecosystem; no species of conservation value present
Ecological and conservation status of host catchment	Near-natural catchment; endangered species are present	Modified catchment; legally protected species are present	Highly modified catchment; no species of conservation value present
Fishery value of the infested water	Water is a nationally important recreational fishery of high socio-economic value	Water is a regionally important recreational fishery of high socio-economic value	Lake has no significant recreational fishery with negligible socio-economic value
Fishery value of host catchment	Catchment hosts nationally important recreational fisheries of high socio-economic value	Catchment hosts regionally important recreational fisheries of high socio-economic value	Catchment has no significant recreational fisheries

Numbers in brackets are scores that should be tallied for each population of that species. Additional scores may be added to the final score according to the presence of exceptional circumstances

Table 3 Evaluation scheme for the overall score obtained from Table 2

Score	Overall risk ranking of population to wider environment	Recommended management action for the population
<7	Low	Do-nothing; exit framework
7–12	Medium	Control and containment; assess method in Module 3
>12	High	Eradication; assess method in Module 3

fishery value of the infested water and receiving catchment (Tables 2, 3). These criteria are ranked as low, medium or high risk, according to a series of definitions. In practice, the criteria are collected by the user via a number of sources; for example, the connectivity of the water body to its receiving catchment may be investigated remotely using GIS tools and through site visits, the conservation status of the waters concerned can be identified through existing conservation designations according to local jurisdiction, and the fishery value of the resources assessed according to records of the species present, current fishery performance and value as assessed by, for instance, fishery rental values and mean annual angler visits.

The criterion scores are then totalled and the total score is used to determine the required management action for the population and site in question (Tables 2, 3). This total score may be adjusted by the assessor if warranted by exceptional circumstances (e.g. +1 for low importance through to +5 for high importance). For example, the wider ecological threat from the dispersal of a species, such as through disease transmission or disruption to ecosystem services, may be of particular concern and warrant an elevated total score, as could a high potential for unregulated anthropogenic dispersal. Alternatively, there may be political reasons why management action is taken that are not necessarily justifiable according to the receiving water and catchment characteristics (e.g. it is the first confirmed occurrence in the wild of the species in the country). The final output indicates the recommended management action for the species/population/site combination from: 1) no further management action necessary; 2) contain and control the population using necessary means; and 3) eradicate the population using an appropriate method. The potential impacts of implementing this output are then assessed in Module 3.

Module 3: impact of the management action

Impact assessment of the management action (3a)

Where the commensurate management action is eradication (*cf.* Module 2), then recent case studies suggest that piscicide-based operations, such as rotenone application, provide a high chance of extirpating the target species, particularly when applied to fish populations in enclosed water bodies (Britton and Brazier 2006; Britton et al. 2008, 2010a). However, it may result in, for example, undesirable losses of other species (Britton et al. 2010a). Correspondingly, before implementation, any proposed action should be assessed in this Module to identify the potential impacts of the action. The primary objective is to indicate the potential severity and likelihood of the management action impacting non-target species and the ecosystem characteristics and services, as well as the likely effect on the policy objectives and the restoration of the ecosystem to its pre-introduction state (Table 4).

For each criterion, assessments are made of the severity of the impact and the likelihood of it occurring, with the assessor providing an evaluation of their level of confidence in each response. The data required on the species, ecosystem and ecosystem services for completing the module should be collected through site visits with appropriate biological and chemical monitoring, and use of expert opinion where required. The inclusion of confidence rankings in the subsequent assessments is important as it provides decision makers with a guide as to the extent of supporting scientific evidence associated with the responses, thus identifying gaps in knowledge. As the confidence rankings are subjective evaluations provided by the assessor, they can also be used to evaluate patterns in the assessor confidence (Copp et al. 2009). Indeed, uncertainty analysis is used frequently in risk assessment procedures (Copp et al. 2005b; Baker et al. 2008), where uncertainty (i.e. low confidence in responses) has two potential sources: variability and incertitude (Hayes et al. 2007). For example, when rotenone application is considered, variability arises from the natural variation between fishes to rotenone toxicity (Allen et al.

Table 4 Predicted severity, likelihood and uncertainty of detrimental impacts, and their mitigation, of eradication by rotenone for the case studies of *Pseudorasbora parva* in North West England (first score in column) and Western England (second score in column) and *Pimephales promelas* (third score in column)

	Criteria	Severity[a]	Likelihood[b]	Confidence[c]	Severity of mitigated impact[d]
Species	Population of protected native fishes	0, 0, 0	0, 0, 4	0, 3, 3	0, 0, 0
	Population of non-protected native fishes	4, 4, 0	4, 4, 4	1, 2, 3	2, 0, 0
	Populations of aquatic mammals	1, 0, 0	3, 4, 4	2, 2, 2	1, 0, 0
	Populations of aquatic birds	1, 0, 0	2, 4, 4	2, 2, 2	1, 0, 0
	Populations of amphibians	3, 2, 3	3, 4, 4	3, 3, 3	3, 0, 3
	Aquatic invertebrate communities	2, 2, 0	4, 4, 4	2, 3, 3	2, 0, 0
	Aquatic macrophyte communities	1, 1, 0	3, 4, 4	2, 3, 3	1, 0¸ 0
Ecosystem	Physical habitat	2, 4, 0	3, 4, 4	3, 3, 3	2, 0, 0
	Chemical water quality	4, 3, 0	4, 4, 4	2, 3, 3	3, 0, 0
	Biological water quality	2, 3, 0	4, 4, 4	2, 3, 3	2, 0, 0
	Ecosystem functioning	3, 4, 0	3, 4, 4	4, 3, 3	3, 0, 0
Ecosystem services	Impact on recreational fishery performance	1, 2, 0	4, 4, 4	1, 3, 3	1, 0, 0
	Impact on recreational fishery income	2, 2, 0	4, 4, 4	1, 3, 3	2, 0, 0
	Impact on water sports other than angling	0, 0, 0	0, 4, 4	0, 3, 3	0, 0, 0
	Impact on non-recreational based ecosystem services	2, 0, 0	2, 4, 4	2, 3, 2	2, 0, 0
Outcome	Impact of management action failure on policy objectives	4, 4, 1	3, 3, 2	3, 3, 3	n/a, n/a, n/a
	Impact of management action failure on the ecosystem and native species	4, 4, 1	2, 3, 1	2, 3, 3	n/a, n/a, n/a

[a] Severity of potential impact (negligible = 0; low = 1; moderate = 2; high = 3; very high = 4)

[b] Likelihood that impact occurs: highly unlikely = 0; unlikely = 1; moderately likely = 2; very likely = 3; highly likely = 4)

[c] Confidence of assessor in their responses (adopted from IPCC, 2005): 0: 2 out of 10 chance; 1: 5 out of 10 chance; 2: 8 out of 10 chance; 3: 9 out of 10 chance

[d] Chance of a mitigation action reducing the severity and likelihood of impact: 2 out of 10 chance: 0; 5 out of 10 chance: 1; 8 out of 10 chance: 2; 9 out of 10 chance: 3

2006; Britton and Brazier 2006) and incertitude from missing data which inhibits completion of the module or where sampling of the faunal communities has been insufficient to reduce the uncertainty (Table 4).

There is a range of options to deal with uncertainty in risk analysis and approaches including mathematical models and simulations that incorporate the likelihood of occurrence and the magnitude of impact (Hayes et al. 2007; Baker et al. 2008). Here, given the use of a relatively small number of criteria with a limited range of options and its applied nature, a simple scoring scheme was applied (Table 4). However, the incorporation of uncertainty provides the opportunity for more complex methodologies to be adopted by other users, and where it is adapted to build in more complexity then modelling approaches may be more appropriate. The initial aim of the uncertainty analysis is to identify those criteria for which the assessor acknowledges that confidence is low (scores of 0 and 1) and then identify and implement approaches where it can be increased through, for example, reducing incertitude by increased sampling of faunal communities (*cf.* Module 3b; Table 4).

Mitigation of the impacts (3b)

Having identified the severity and likelihood of the proposed option causing an undesirable impact (i.e. scores of 3 or 4; Table 4), Module 3 then offers the opportunity to consider mitigation measures that could reduce these impacts to an acceptable level (scores <2; Table 4). If mitigation cannot reduce the severity and likelihood, then the decision must be made whether or not the management action may proceed. The purpose of this mitigation analysis is to provide an output of the overall confidence rating of the module by way of a cumulative score of the confidence assessments. Cumulative scores of 0–20 indicate low confidence in the assessments of the risks, those of 21–30 indicate moderate confidence, those of 31–40 indicate high confidence, and those of 41–48 indicate very high confidence. Thus, cumulative scores of <30 suggest the assessor has been unable to complete the module with sufficient confidence to enable the proposed action to proceed without further review or data collection and evaluation.

The output of the module is thus an identification of the potential impacts of the management action, the mitigation action that may reduce this and the cumulative level of confidence around this. Where the impacts are assessed as low or negligible, or have been reduced to these levels through mitigation, and the cumulative confidence score is >30, then the action can proceed. Where more severe impacts are predicted and mitigation cannot satisfactorily reduce these, then a risk-based decision is required to ascertain whether it is appropriate for the management action to proceed and an alternative approach may be necessary (Fig. 1). Consequently, scores for the case studies (Table 4) do not require comparison between them but should be used to identify the severity, likelihood and cumulative confidence of the management action on the species, ecosystem, ecosystem services and outcome for each site.

Module 4: cost of the management action

The final module assesses the cost of eradication in relation to the alternative of control and containment. Given the assessed risk of the species and population in Modules 1 and 2 then an option of 'no management action' is not considered. Studies on the eradication of invasive fish using rotenone application in England and Wales have already demonstrated that the approximate cost is £2 per m^{-2} of water surface treated (Britton et al. 2008, 2010a). This figure does not include the amenity loss (if the receiving water is used as a recreational fishery) or the economic loss (if the receiving water is used as an aquaculture site) that would be incurred through the rotenone application. Nor does it include the cost of any replacement fish or broodstock. Consequently, the cost must account for both operation and the predicted economic losses that will be incurred. These costs can then be compared against the long-term cost of control and containment that may be providing an economically efficient option in the short-term but may actually provide a high cumulative cost in the longer term. The cost of control and containment should incorporate all man-power costs charged at their standard rate, the cost of maintaining barriers to prevent dispersal opportunities and all costs related to removal operations.

An example of the one-off cost of eradication using rotenone (and assuming success) against the long-term cost of control and containment is demonstrated here where the cost estimates are based on the *Pseudorasbora parva* eradication case study of Britton and Brazier (2006). The area of water to be treated by rotenone was 2.2 ha, had ≈1,000 angler visits per annum (p.a.) with each paying £8 per day and the replacement cost of the fish being lost through rotenone application was estimated at £10,000 (U$15,000). It was anticipated that the disruption to the fishery would last ≈12 months, and following the stocking of replacement fish, angler visits per year would initially be at 50% of their original figure but will increase by 10% p.a. until they reached their pre-eradication level. The

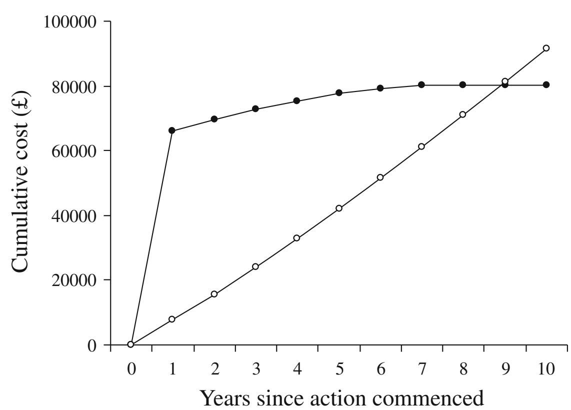

Fig. 3 Cumulative cost of a rotenone-based eradication operation and a control and containment strategy for managing *Pseudorasbora parva* in a lake in north West England of 2.2 ha in area. Please refer to the text for details on how the figures were derived

cost of control and containment was based on: 1) the annual cost of 12 (if the water is <3 ha) and 16 (if >3 ha) man-days charged at £300 per day ($450), with inflation at 2% per annum, for the purposes of containing and controlling the population; 2) the reduction in amenity value that may be incurred by the invasive fish (assuming it is a pest), estimated as an on-going 10% p.a. reduction in angler visits; and 3) the annual cost of supplementing the fish stock through enhancement stocking to mitigate for the effects of the invader on fishery performance (£500 p.a.). Using these values, the cumulative cost of long-term control and containment exceeded the cost of a one-off eradication operation in approximately 9 years, but with the additional benefit of ecological and fishery restoration (Fig. 3).

Application case studies

Case study 1: eradication of *Pseudorasbora parva* from a lake in north-west England

Specific details relating to this eradication operation are available in Britton and Brazier (2006). Following detection of *Pseudorasbora parva* in the lake in 2002, a rotenone based eradication operation commenced in March 2005. Subsequent evaluation to 2010 suggested that it was successful in eradicating *P. parva* from the lake and removed its threat of dispersal into its river catchment (Britton and Brazier 2006) at a cost of approximately £61,000 (Britton et al. 2008).

The spatial distribution of *P. parva* in England and Wales was (and remains) restricted (11–50 known sites; Fig. 2; Table 1) and falls in the highest risk category according to its FISK score. This score results from their history of proving highly invasive following introduction and their ecology providing significant potential for the colonisation of new waters (opportunistic life history, high plasticity in life history traits, high tolerance to degraded habitats; Britton et al. 2008). Thus, in combination, the output from Module 1 is 'D', i.e. it remains a high priority species requiring immediate management action. In Module 2, the score obtained by this *P. parva* population, following inclusion of the highest 'exceptional circumstance' score, was 17 (Table 5), thus eradication was the commensurate management action. As the water body could not be drained, the only feasible method was rotenone application (Britton and Brazier 2006). The initial output of Module 3 indicated there were two criteria that resulted in a high likelihood of severe impact (Table 2), with mitigation measures (removal and quarantine of non-target fishes for the duration of rotenone treatment) reducing the potential adverse impacts to an acceptable level (Britton and Brazier 2006). This, however, was not possible for amphibians. Thus, the highly likely impact on their populations was the only potentially severe detrimental impact (Table 3). The confidence score was sufficiently high to indicate the assessor was highly confident in their overall assessment (Table 4). Thus, providing that managers were comfortable with the potential impacts on amphibians then Module 3 suggested the eradication could proceed. Module 4 indicated that the cumulative cost of long-term control and containment of the population would exceed eradication in only 4 years (water size was 2.2 ha). Thus, retrospective application of the modular scheme indicated that the decision to eradicate this population of *P. parva* by rotenone was the commensurate management response and use of rotenone had a high confidence of causing limited detrimental impacts to the receiving water and so was appropriate to apply. Indeed, there were no reports of amphibian mortalities following rotenone application and spawning was observed to occur in subsequent weeks.

Case study 2: eradication of *Pseudorasbora parva* from a lake in West England

Specific details relating to this eradication operation are available in Britton et al. (2008). Following detection of *P. parva* in the lake of 0.68 ha in March 2005, their risk of dispersing into the adjoining river catchment was assessed as high, suggesting eradication was necessary to protect the waters downstream from their dispersal. Owing to the presence of a non-native fish parasite in the fish community, a drain-down and liming operation was deemed more suitable than rotenone application as this would break the parasite lifecycle. This was completed between February and August 2006, and evaluation in the 4 years since the action was taken suggests the eradication was successful and the threat of *P. parva* dispersal into the river catchment was been eliminated.

The output from Module 1 was that *P. parva* is a high priority species requiring immediate management

Table 5 Output of Module 2 for the case studies of *Pseudorasbora parva* and *Pimephales promelas*

a) *Pseudorasbora parva* in NW England

Criterion	Interpretation and score
Species' relative risk ranking	High or medium risk species that is restricted in distribution (2)
Potential for species dispersal	Water has a direct connection to a river catchment (2)
Ecological and conservation status of infested water	Highly degraded ecosystem; no species of conservation value present (1)
Ecological and conservation status of host catchment	Near-natural catchment; endangered species are present (3)
Fishery value of the infested water	Water is a regionally important recreational fishery of high socio-economic value (2)
Fishery value of host catchment	Catchment hosts regionally important recreational fisheries of high socio-economic value (2)
Exceptional circumstances index	High: 5; species was previously absent or very localized in the North of England, and the catchment of the infested site connects to the Lake Windermere system
	Overall score = 12 + 5 = 17

b) *Pseudorasbora parva* in W England

Criterion	Interpretation and score
Species' relative risk ranking	High or medium risk species that is restricted in distribution (2)
Potential for species dispersal	Water is located in the flood plain (3)
Ecological and conservation status of infested water	Highly degraded ecosystem; no species of conservation value present (1)
Ecological and conservation status of host catchment	Near-natural catchment; endangered species are present (3)
Fishery value of the infested water	Water is a regionally important recreational fishery of high socio-economic value (2)
Fishery value of host catchment	Water is a nationally important recreational fishery of high socio-economic value (3)
Exceptional circumstances index	0: there are no exceptional circumstances
	Overall score = 14

c) *Pimephales promelas*

Criterion	Interpretation and score
Species' relative risk ranking	High or medium risk species that is restricted in distribution (2)
Potential for species dispersal	Lake is fully enclosed with no opportunity for natural dispersal (1)
Ecological and conservation status of infested water	Naturally functioning ecosystem; legally protected species present (2)
Ecological and conservation status of host catchment	Modified catchment; legally protected species are present (2)
Fishery value of the infested water	Lake has no significant recreational fishery with negligible socio-economic value (1)
Fishery value of host catchment	Catchment hosts regionally important recreational fisheries of high socio-economic value (2)
Exceptional circumstances index	Low: 1; although the first confirmed report from 'the wild', species has been present without dispersal for >10 years in a gated private property that is outside the flood zone
	Overall score = 10 + 1 = 11

Refer to Table 3 for interpretation of the overall scores

actions (*cf*. Case study 1). As the score obtained by this *P. parva* population in Module 2 was 14, eradication was the commensurate management action, with draining and liming the preferred option as previously described (Tables 3, 5). The initial output of Module 3 indicated there were severe impacts associated with non-protected native fishes, the physical habitat and ecosystem function; the fishes had to be removed and euthanized due to the parasite infection, and the physical habitat and ecosystem function would be severely disrupted by water removal and draining for over 6 months (Table 2). There were no mitigation measures that could minimise these impacts. The confidence score was sufficiently high to indicate the assessor was highly confident in their overall assessment (48; Table 4). Thus, Module 3 suggested the eradication could be undertaken, and Module 4 indicated that the cumulative cost of long-term control and containment of the population would exceed eradication in 6 years. Here, the cost of the drain down exercise was significantly higher than application of rotenone in the same surface area of water, with the final cost of the operation calculated as £50,800. Thus, retrospective application of the modular scheme indicated that whilst the decision to eradicate this population of *P. parva* by drain-down was the commensurate risk management response due to the high risk of their dispersal into a major river catchment, its drain-down approach would invoke substantial impacts on some aspects of the pond ecosystem. Notwithstanding, this ecosystem was already modified by the regular stocking of fish such as common carp *Cyprinus carpio* into the lake for the enhancement of angling.

Case study 3: eradication of *Pimephales promelas* from a former aquaculture site in north-east England

This eradication operation was completed in February 2010 and consisted of rotenone application to two small aquaculture ponds that were infested with established feral populations of fathead minnow *Pimephales promelas*, a North American cyprinid that had been sold for at least a few decades in the aquarium trade in its ornamental (rosy red) variety. Other than garden pond populations (Parrott et al. 2009), these fish represented the only known established feral populations in England and Wales. Their introduction was believed to have been as a contaminant of a consignment of young-of-the-year golden orfe, the ornamental variety of ide *Leuciscus idus* (Zięba et al. 2010). Detection of the population was in August 2008 (Zięba et al. 2010) and research on their population commenced in 2009 (unpublished data). Whilst it remains too early to evaluate its overall success, *P. promelas* have not been reported since rotenone application, with other fishes now present having been intentionally introduced (*Silurus glanis*).

Pimephales promelas has isolated populations in England and Wales (1–10 known sites). In combination with their FISK score, they are a medium priority species for which management actions are desirable but not essential (Fig. 2; Table 1). Module 2 provided an initial score of 10, meaning that control and containment was the commensurate response (Tables 2, 3, 5). This was because the site was outside the flood plain, relatively secure and the species had been present for >10 years with no known dispersal. Their scoring in the exceptional circumstance index is relatively subjective; given their low chance of natural dispersal and previous ornamental availability (a known introduction pathway; Copp et al. 2005c) then the score is arguably low, resulting in a maximum score of 11, i.e. control and containment remains the commensurate response (Table 4). Alternatively, as the only known feral population in the wild (at that time), the exception score could be rated as medium (3), raising the score to 13 where eradication is the commensurate response. Irrespective, assessment of rotenone application in Module 3 suggested its severity and likelihood of occurrence of impacts were primarily negligible for the criteria, except for the elevated risk of collateral impacts on amphibia (where losses were apparent; P. White pers. comm.), with a very high confidence score of 48 (Table 3). Module 4 indicated the cumulative cost of control an containment exceeded eradication in two years. Thus, whilst the initial assessment suggested control and containment was the commensurate approach (Module 2), eradication by rotenone has provided a cost-effective option in the long-term (Module 4), albeit with some short-term collateral damage.

Discussion

The management of introduced species is fundamentally constrained by aspects including limited knowledge on the species and their distribution, effective methods for managing populations, and limited resources (Genovesi 2005; Edwards and Leung 2009; Britton et al. 2010a). This is further impeded by the eradication of established invaders remaining relatively rare, with control efforts varying enormously in their efficacy (Mack et al. 2000). It has been argued that successful control of established non-native populations depends more on commitment and continuing diligence than on the efficacy of specific tools themselves; control of introduced populations is most effective when it employs a long-term, ecosystem-wide strategy rather than a tactical approach focused on battling individual invaders (Mack et al. 2000). The basis of this modular scheme was, however, to prioritize those species that are still early in their invasive pathway and will potentially incur severe impacts in the environment. By identifying the species of highest priority, management actions can be initiated to impede their further establishment through prompt inhibition of their dispersal. Thus, we suggest that for high-risk non-native fishes (of being invasive), which are early in their invasion pathway, species-specific management approaches may be preferable, as demonstrated by the case of the distribution of invasive *Pseudorasbora parva* being successfully controlled in the UK (Britton et al. 2010a; Gozlan et al. 2010a, b). This is also consistent with the recommendation of Simberloff (2009) of detecting invasions early (in this case, when still spatially restricted) and acting quickly to eradicate it. For species that have already achieved a large spatial distribution, their assessment in this scheme of being of only medium risk, irrespective of their potential impacts, are more in agreement with Mack et al. (2000) given the almost impossible task of eradicating invasive fish from large spatial areas. Indeed, the management of common carp in England and Wales revolves around enhancing their populations for angling exploitation rather than controlling their distribution, despite their very high FISK score and their considerable spatial distribution (Britton et al. 2010b).

In the risk management of introduced species, managers must resolve complex ecological, socio-economic and ethical arguments across a multitude of conflicting stakeholders and authorities to determine the optimal actions (Stokes et al. 2006; Finnoff et al. 2007). Frameworks, such as that described here, enhance resolution of these arguments and provide a more quantitative and transparent output. However, it only provides an indication of how the risk could be managed according to the assessment and there may be occasions when it is decided to manage the risk using an alternative approach. This was demonstrated by Case study 3, where initial assessment suggested control and containment was the commensurate response, but eradication by rotenone had been used to manage the risk. This operational outcome raised considerable debate among managers and decision-makers, mainly due to the described issues relating to the exceptional circumstance score (issues of perceived vs. likelihood of occurrence; *cf*. Case study 3). However, eradicating the population removed the only known feral population in England and Wales outside of captivity, albeit one with low ability to disperse naturally; it also resulted in amphibian losses and prematurely concluded the research that was informing the risk analysis of *P. promelas*.

An alternative risk management approach is the recent rapid assessment framework developed by Edwards and Leung (2009), which determines eradication feasibility even where data are limited. Their quantitative model also estimates the necessary effort and timing, and of the size of the target area, required for eradication (Edwards and Leung 2009). When applied to a tunicate (*Ciona intestinalis*) invasion in Canada, their cost—benefit analysis suggested that only a $\geq$16% chance of eradication success would be sufficient to make that proposed action worthwhile to attempt. The scheme developed here was not developed in these terms, given that options to eradicate invasive fish remain limited to specific circumstances, such as when their populations are still restricted to lentic habitats and have yet to disperse into lotic habitats (Britton et al. 2008). Correspondingly, the most effective and successful eradication method is currently rotenone application (Britton and Brazier 2006; Britton et al. 2010a). However, owing to a multiple of conflicting factors, rotenone applications in England and Wales are normally applied in February and March only. Thus, the outputs of Edwards and Leung (2009) relating to timing, size of target area and success feasibility are largely superfluous in a UK context and decisions are restricted to whether it is actually feasible to apply rotenone to the water body (*cf*. Module 3).

What this modular framework cannot do, however, is assist compliance with other aspects of best-practice relating to invasive species control. For instance, Simberloff (2009) also suggests that there should be the existence of a person or agency with the authority to enforce cooperation of invasive species management and project leaders must be energetic, optimistic, and persistent in the face of occasional setbacks. Moreover, funding of schemes remains problematic, and in England and Wales this is likely to become even more problematic in the face of imminent public spending cuts between 2010 and 2015. Thus, even where this scheme may suggest action is necessary, the previous reliance of eradication schemes in England and Wales on small teams of dedicated people to deliver outcomes (*cf*. Britton et al. 2010a) may become more difficult to achieve in an era of restricted resources. Options may then have to include utilising manual and unpaid (volunteer) labour as has been utilised in schemes in parts of England & Wales (e.g. Sutton-Croft 2010) as well as elsewhere in the world (Campbell and Carter 1999; Simberloff 2003, 2009).

In summary, the development of this multidisciplinary and modular risk-based framework assists the management of introduced fishes within England and Wales. The scheme can assess non-native fish that have been introduced 1) accidentally as a contaminant, such as *P. parva* (Britton et al. 2008), *P. promelas* and sunbleak *Leucaspius delineatus* (Zięba et al. 2010); 2) purposely, but where risk assessment processes were not in place at that time, such as the European catfish *Silurus glanis* (Britton et al. 2007), prior to when non-native species threats were recognised, and the grass carp *Ctenopharyngodon idella* (Stott 1977), when assessments of proposed non-native fish introductions were first initiated; and 3) without adherence to fish introduction legislation, such as bighead carp *Hypophthalmichthys nobilis* (Britton and Davies 2007) and numerous aquarium species (Zięba et al. 2010). It provides a prioritised list of those introduced fishes and their populations where actions are both necessary and justifiable, and then impact assessments of the different management actions available for those populations. It may be adapted for prioritising management actions on introduced fishes elsewhere in the world or for use with other faunal groups. It should thus assist objective decision-making and enable better prioritisation in resource expenditure that delivers more robust conservation outcomes. To this end, an electronic (Excel® Visual Basic®) version of this scheme is currently being developed, and is expected to be available later in 2011 to complement the existing library of decision support tools (Cefas 2011).

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