

Confronting the risks of large-scale invasive species control

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Large-scale invasive species control initiatives are motivated by laudable desires for native species recovery and economic benefits, but they are not without risk. Management interventions and policies should include evidence-based risk-benefit assessment and mitigation planning.

Invasive species are a leading cause of biodiversity loss¹ and arresting their adverse effects is a priority for governments worldwide. Programmes aimed at controlling or eradicating invasive species are being deployed across vast geographic areas — from islands to coastal ecosystems and even whole continents (Fig. 1). The European Union (EU) recently adopted a list of invasive species (Regulation 2016/1141), which requires member states to prevent, control or eradicate 37 species. Meanwhile, Australia plans to kill two million feral cats *Felis catus* by 2020 as part of its Threatened Species Strategy, and as early as 2018 plans to control invasive common carp *Cyprinus carpio* by releasing a virus² across one million square kilometres of the country's largest river system. In the United States, there has been a surge of activities aiming to legalize unlimited harvest of invasive fishes (Fig. 1). In what is perhaps the most ambitious proposal so far, New Zealand formally announced seed funding in 2016 to begin a national eradication of at least seven invasive mammals over the next 50 years³. Although these initiatives are motivated by laudable desires for native species recovery and economic benefits, they are often highly politicized and carry substantial risks which must be carefully assessed against the potential benefits.

Emerging biotechnologies, notably CRISPR–Cas9 gene drives⁴, may increase the feasibility of large-scale control with genuine potential for continental-scale eradication of unwanted populations or species. This rapidly progressing technology now permits engineered genes to be spread throughout populations, even when a trait confers negative fitness. While CRISPR–Cas9 has been trialled in laboratories, it is now being considered to control wild mosquitos and

can be adapted to modify the genomes of taxa ranging from insects to humans⁴. This technology has tremendous potential to solve environmental, agricultural and human health problems associated with invasive species, but caution, policy reform and ecological risk assessment have been advised following a National Academies of Sciences, Engineering and Medicine review⁴.

Successful eradications over the past 20–30 years have resulted in many positive and long-term biodiversity outcomes⁵, but control of established invasive species can produce unanticipated and undesirable results that must be considered and mitigated (Box 1). Such undesirable consequences have arisen when invasive species perform unexpected functional roles in food webs, or when they provide habitat or support ecological processes important to native species⁶. Perverse food web outcomes include changes that increase rates of predation on, or limit resources available to, native species^{7,8}. Undesirable consequences can also include biophysical changes, such as loss or alteration of habitat, or modification of an ecological process such as sediment stability, nutrient transfer, seed dispersal or pollination that was being supported by the invasive species^{6,9}. In extreme cases, controlling invasive species can degrade ecosystems, requiring expensive reparatory actions¹⁰.

To avoid undesirable outcomes, large-scale invasive species control programmes (Fig. 1) will need to carefully assess and manage the risks and benefits to society and environments, with careful consideration of the whole system (Box 1). California's Channel Islands provides a prime example of how consideration of risks can help avoid potential negative outcomes of invasive species control. Here, the eradication of

feral pigs *Sus scrofa* unexpectedly threatened the survival of multiple subspecies of the critically endangered island fox *Urocyon littoralis*¹¹. Abundant piglets attracted golden eagles *Aquila chrysaetos* to the island, which preyed on both pigs and native foxes. Until the 1960s and the widespread use of DDT, golden eagles were likely excluded from the islands by bald eagles *Haliaeetus leucocephalus*, which preyed on fish and carrion but not on foxes. This string of species interactions necessitated translocation of golden eagles off the islands and re-introduction of bald eagles to prevent increased predation on foxes following pig control¹². The subsequent dramatic and rapid increase in island fox populations demonstrated the transformative potential benefits of invasive species control, but simultaneously highlighted the substantial risks and mitigation measures that needed to be carefully managed following the removal of abundant and ecologically influential invasive species.

Science-policy implementation gap

There is currently a wide gap between science — which has demonstrated the potential for undesirable ecological and social outcomes of invasive species control (Box 1) — and the on-ground implementation of many invasive species control programmes which fail to recognize and mitigate the effects of unwanted outcomes. Ecological disasters, such as the release of cane toads *Bufo marinus* in Australia, the use of tributyltin to prevent biofouling on vessels, or the global landscape-scale application of DDT — all to control pests — have stimulated environmental protection policies in many countries. These policy safeguards focus on threats to the environment, including the

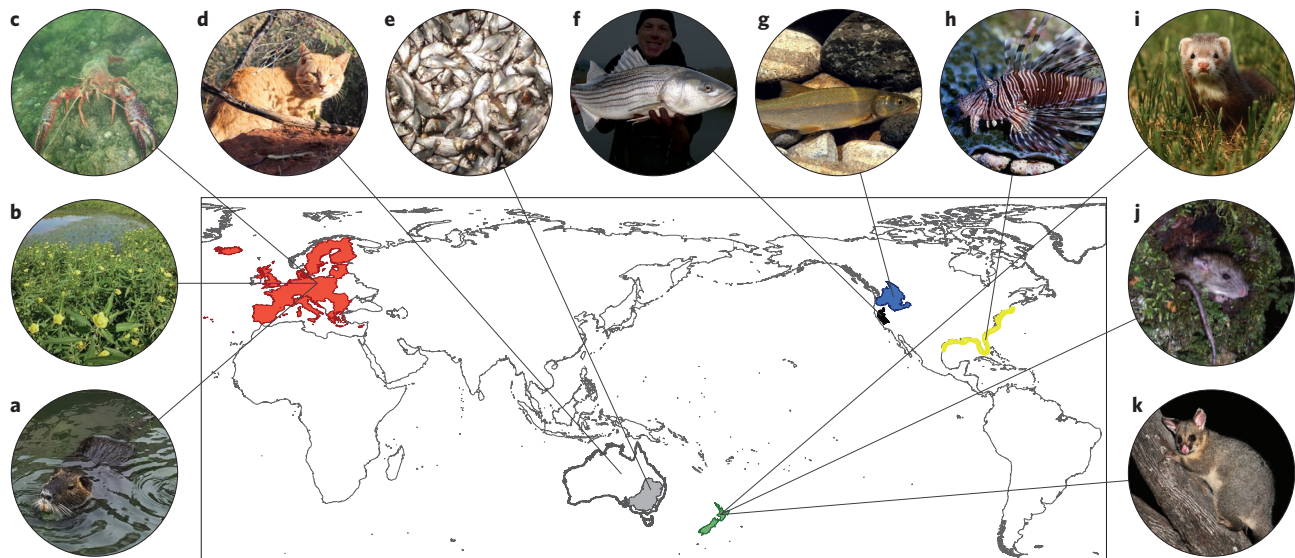


Figure 1 | Large-scale initiatives aiming to control invasive species. **a–c**, The European Union (red) list of ‘invasive alien species’ was adopted in 2016 and includes 14 plants and 23 animals that are subject to management measures across the 28 member nations covering an area of approximately 4 million km². **d,e**, Australia (grey outline) announced that it intends to release a biocontrol agent — cyprinid herpesvirus-3 — as early as 2018 into invasive carp populations across more than 1 million km² of the Murray–Darling basin (grey fill) and then the rest of the continent. As part of its Threatened Species Strategy, Australia also proposes to kill 2 million feral cats by 2020. **f–h**, In the United States, ongoing efforts have legalized and occasionally provided incentives for unlimited fishing of invasive predators such as striped bass in the Sacramento River (black) in California, northern pikeminnow native to the Columbia River (blue), invasive lionfish on the Atlantic and Gulf coasts (yellow) and invasive warm-water fishes across the west coast of the United States. **i–k**, The New Zealand (green) government announced in 2016 US\$20 million seed-funding to begin eradicating three groups of terrestrial invasive mammals: three mustelids, three rodents and the Australian brushtail possum, by 2050. Publ. note: Springer Nature is neutral about jurisdictional claims in maps. Species pictured: nutria (*Myocastor coypus*, **a**), largeflower primrose-willow (*Ludwigia grandiflora*, **b**), red swamp crayfish (*Procambarus clarkia*, **c**), feral cat (*Felis catus*, **d**), common carp (*Cyprinus carpio*, **e**), striped bass (*Morone saxatilis*, **f**), northern pikeminnow (*Ptychocheilus oregonensis*, **g**), lionfish (*Pterois miles*, **h**), ferret (*Mustela furo*, **i**), black rat (*Rattus rattus*, **j**), Australian brushtail possum (*Trichosurus vulpecula*, **k**). Photo credits: Julien Cucherousset (**a,c**), Jean-Patrice Damien (**b**), Tim Doherty (**d**), Clayton Sharpe (**e**), Phil Antipa (**f**), William Mullins/Alamy Stock Photo (**g**), Brand X Pictures (**h**), Tierfotoagentur/Alamy Stock Photo (**i**), Andrea Byrom (**j**), Ingo Oeland/Alamy Stock Photo (**k**).

risks of invasive species control methods (for example, pesticides, toxins, biocontrol), but often overlook the ecological and social risks of successfully controlling the established invasive species. For example, some scientists have expressed concern about Australia’s carp eradication programme¹³, while those leading the initiative suggest that it is a safe and effective method of biocontrol¹⁴. The risks highlighted in ref. ¹³ included but were not limited to negative effects on water quality and drinking water as tonnes of dead carp are likely to foul waterways. At the time of this publication an independent evidence-based assessment of the risks and benefits of carp control using the virus has not been undertaken.

In order to make judgments about whether or how to proceed with large-scale invasive species control (Fig. 1), we argue that independent evidence-based assessment of both risks and benefits is imperative (Box 1). Decisions about invasive species control are often politicized, or are not independent and evidence-based. Similar to the advice provided in ref. ¹⁵, we suggest that risk–benefit assessments should: (1) be

undertaken by research organizations independent of the group proposing invasive species control; (2) consider the perceived risks and benefits of a range of stakeholders from scientists to managers and the general public; (3) include peer-reviewed and expert estimates of the potential benefits and the likelihood and severity of risks; and (4) be transparent and made freely available to the public, including the peer review itself. Although ecosystem models rarely produce clear-cut predictions, they can forecast a range of scenarios¹⁶ including the risks of doing nothing. These can allow decision-makers to proactively anticipate risks and make informed decisions about how to avoid adverse outcomes.

Following an independent evidence-based assessment, decision-makers may choose either to avoid, mitigate or accept the risks. For example, decomposition of tonnes of dead carp following the release of a virus may trigger short-term hypoxia and spikes of nitrogen, and cause native fish kills, but such risks could be worth accepting and mitigating if energy that currently flows to support vast populations of invasive carp

enhances productivity of native fishes, recreational fisheries or threatened species in the longer term. However, to make such decisions it is imperative that quantitative and qualitative estimates of the range of plausible benefits are also made so that they can be compared against the risks.

While we urge caution and ecological risk–benefit assessment for activities targeting established invasive species, we support fully the need for no delay in preventative actions and interventions focused on recent invaders, such as non-native lionfish *Pterois miles* and *P. volitans* on the east coast of the United States (Fig. 1), which are less likely to have become embedded in ecosystems (Box 1). Undesirable ecological outcomes following control of established species have been well known for some time⁷, but policies targeting established invasive species usually do not require mandatory pre-assessment or mitigation against broader risks of removing these species. For instance, the recent EU list of invasive alien species and requirements (Regulation 1143/2014) specifies that: “When applying

Box 1 | Key considerations for scientists, managers and decision-makers embarking on large-scale invasive species control.

Is there an evidence base for ecological benefit, or harm, from the method of control and removal of the invasive species? The decision to engage in invasive species control should be based on peer-reviewed empirical evidence indicating a high likelihood of ecological benefit and a low likelihood, or low severity, of harm. This starting point seems obvious, but is essential to ensure that actions are evidence-based; not based on poor science, politics or conventional wisdom (for example, “invasive species are bad”).

What other invasive species might benefit from successful control of the target species? The release of non-target invasive species via reduced competition⁷, or predation including meso-predator release¹⁸ is a common occurrence following control or eradication of single species.

Is the target invasive an important food source for native or other invasive species? Owing to their abundance and wide-spread distribution, invasive species can represent a fundamental part of the diet of native⁶, and other invasive animals which may switch to feeding upon other native⁶ or endangered species¹¹ following control. If so, how long would the effect last?

Does the invasive species provide important habitat for native species? Native and sometimes threatened animals

can become reliant on exotic plants and trees for habitat^{7,9}, especially when native habitat has been cleared or is highly degraded. If so, what opportunities exist for native species to replace the lost habitat?

Will the removal, or death, of the invasive species alter ecological processes supporting native species or ecosystem services? Undesirable consequences for native species and for people can arise following control from the loss or modification of ecological processes such as sediment stability, nutrient transfer, seed dispersal or pollination that were being supported by invasive species^{6,7}.

What is the time since invasion and the spatial extent of the species' distribution? With increasing time since invasion and increasing spatial extent, non-native species are more likely to have become embedded in ecosystems and effective control is less likely¹⁹.

What will be the speed and spatial extent of invasive species population reduction (weeks, months, years, or decades)? Rapid removal⁹ or mortality events of invasive species, particularly across large areas, may provide insufficient time for native species to acclimate to changing conditions.

Are native species or ecosystems within, or adjacent to the control area, protected

by local, national or international policies? The presence of a protected species, or ecosystem alone should initiate a formal environmental risk assessment process in most western countries, although invasive species control programmes may currently be exempt owing to a presumption of no risk. The presence of native species within or adjacent to the area is also important to consider in regards to opportunities for recovery.

Is the method of control reversible? If unwanted outcomes arise, then it is possible to prevent further damage if the method of control (for example, shooting) can be stopped or reversed. If the method of control is irreversible (for example, biological control) then potential adverse outcomes may not be possible to stop²⁰.

What pre-existing ecological or socio-economic constraints may inhibit the recovery of native species following control? The goal of large-scale invasive species control is recovery of native species and benefits to people. Even if control is successful, complementary management actions (for example, eradicating other invasive species; reinstating natural river flow regimes; reintroducing native species) are likely to be required in order to achieve desired goals for recovery.

management measures [...] member states shall have due regard to human health and the environment, especially non-target species and their habitats ...” but does not stipulate a mandatory requirement for ecological assessment or mitigation of unwanted outcomes following invasive species removal.

Uncertainty and undesirable outcomes

One obstacle to managing the risks of invasive species control is uncertainty. Uncertainty in how ecosystems will respond to control makes quantitative risk analyses and forecasting challenging. As a consequence, invasive species control policies should evaluate and plan for a wide range of plausible scenarios and incorporate flexibility into management strategies¹⁶. Modern approaches to ecosystem modelling offer powerful tools to incorporate adaptive management scenario planning, and structured decision-making into risk analyses^{12,17}, but these techniques are

generally neglected in policies focused on the removal of invasive species. Assessment using ecosystem modelling can identify where risks and uncertainty are too large to responsibly engage in control, or identify actions that could be undertaken before, during or after control to reduce negative outcomes and uncertainty or enhance benefits to native species and ecosystems^{9,11,12}. Evidence-based assessment of risks and uncertainty is particularly important when control programmes are planned to affect large social-ecological systems (for example, Fig. 1) and when the control method is rapid and irreversible. Rapid or irreversible control methods (for example, the release of a virus or engineered genes) diminish the capacity to change course should unexpected outcomes arise (Box 1).

We welcome large-scale proposals to thwart the adverse effects of invasive species but emphasize that ignoring the risks of controlling established species threatens to

hasten global biodiversity loss, undermine public trust and the value of conservation science and practice. The weight of evidence demonstrating the transformative potential benefits of invasive species eradication is becoming clearer but there is a need now for management action and policy which demands pre-intervention risk-benefit assessment and mitigation planning. The goals of native species recovery and benefits to society are laudable, but the potential risk of harm by large-scale invasive species control must first be assessed using an evidence-based approach and the results carefully considered. Enthusiasm for large-scale control, combined with political pressure to implement these initiatives and with CRISPR-Cas9 gene drive technology⁴ that is on the cusp of implementation, means that the need to bridge the gap between the science demonstrating potential risks and the implementation of invasive species control policies is more urgent than ever. □

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Competing interests

Five of the authors have submitted a grant application to Australia's Fisheries Research and Development Corporation to assess the: 'Ecological, social and socio-economic risks and benefits of releasing koi herpes virus to control common carp, *Cyprinus carpio* in Australia.'