Surrogacy in invasion research and management: inferring "impact" from "invasiveness"

Luke S O'Loughlin[1,2,3*], Ben Gooden[4,5], Jacob N Barney[6], and David B Lindenmayer[1]

Biological invasions are known drivers of biodiversity decline, yet the ecological impacts of invaders remain largely unmeasured in many contexts. Consequently, other measures of a species invasion (eg local abundance) are often used as surrogates (or "proxies") to infer impact on recipient ecosystems. However, the use of surrogates for impact in invasion science and management is often implicit, and frequently lacks the evaluation and validation that characterize surrogate use in other fields. Although there are practical reasons for this, the risks associated with not testing the accuracy, stability, and certainty of surrogates for invasive species impact must be acknowledged. Recognizing the role of surrogacy in invasion science offers previously unappreciated solutions for increasing the quantitative rigor of invasive species impact assessments that inform management decisions.

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Invasive alien species represent major threats to biodiversity through their impacts on recipient ecosystems (Courchamp *et al.* 2017). Despite this, the ecological consequences associated with the success of most alien species remain poorly explored and are seldom quantified (Barney *et al.* 2013; Blackburn *et al.* 2014). Demonstrating and predicting the impacts of invasive species on recipient ecosystems is difficult due to the highly context-specific interactions and drivers that characterize most invasions (Courchamp *et al.* 2017; O'Loughlin and Green 2017b). Closing this knowledge gap represents an ongoing challenge for invasion research and management. Acknowledging this, many researchers have proposed useful approaches for improving direct assessments of impact, including semi-quantitative categorical frameworks (eg Blackburn *et al.* 2014), quantitative metrics that integrate multiple measured effects (eg Barney *et al.* 2013), and predictive tools that use explicit measures of a species' per capita effects (eg the functional [consumption] and numerical [abundance] response of a predator at a particular density of prey; Dick *et al.* 2017). However, direct assessments of impact often do not occur, with researchers and practitioners instead relying on surrogate measures to *infer* unmeasured effects of invasive species on native ecosystems, and inform the prioritization and management of such invaders (Kumschick *et al.* 2012).

In a nutshell:

- Invasive species pose major threats to native species and ecosystems, yet their impacts remain poorly explored and are rarely quantified
- There is a practical need to identify invasive species and prioritize their management based on the magnitude of their impact, meaning easier-to-measure variables (such as an invasive species' local abundance) are widely used to infer unmeasured impacts
- This practice of inferring invasive species impacts from surrogate measures is widespread in invasion science and management, but often lacks the requisite evaluation and validation that is commonplace in other disciplines where surrogates are used
- Greater integration of ideas from surrogate research into invasion ecology offers a previously unrecognized solution to issues related to quantifying, demonstrating, managing, and communicating the ecological impacts of invasive species

Measuring a surrogate (or "proxy" or "indicator") for a target of interest for which direct measurement is difficult is common practice across a broad range of disciplines, from medical research to fundamental ecology and natural resource management (O'Loughlin *et al.* 2018). In ecology, the usual approach is to measure one variable in the ecosystem (eg plant species richness) and use the measurement(s) to infer something unmeasured (eg ecosystem productivity) based on a known relationship, established at an earlier point in time, between the surrogate and the target (Lindenmayer *et al.* 2015). Similar to concepts like biodiversity, the ecological impacts of an alien species are often too complex to be assessed completely (Jeschke *et al.* 2014). Consequently, any meaningful conclusions regarding invader impacts will depend on the surrogate measures used to infer them (Hulme *et al.* 2013).

Because measuring effects through surrogates instead of directly measuring native ecosystem responses (ie the target)

[1]*Fenner School of Environment and Society, The Australian National University, Canberra, Australia;* [2]*School of Environmental Science, Charles Sturt University, Albury, Australia;* [3]*Current address: Department of Ecology, Environment and Evolution, La Trobe University, Bundoora, Australia *(L.OLoughlin@latrobe.edu.au);* [4]*CSIRO Health and Biosecurity, Canberra, Australia;* [5]*School of Earth, Atmospheric and Life Sciences, Faculty of Science, Medicine and Health, University of Wollongong, Wollongong, Australia;* [6]*School of Plant and Environmental Sciences, Virginia Tech, Blacksburg, VA*

necessitates accepting a degree of uncertainty (regarding whether the chosen surrogate is suitable for inferring those effects), the use of surrogates sometimes leads to unwarranted or unqualified inferences (O'Loughlin *et al.* 2018). Relying on surrogates in the assessment of invasive species impacts is not explicitly recognized or discussed in invasion research or management. Therefore, most of the uncertainty and risk associated with how accurately a surrogate represents the ecological impacts of an invader is underappreciated. For example, the abundance of an invader is regularly used to infer unmeasured impacts on the recipient ecosystem (Pearson *et al.* 2016; Essl *et al.* 2017) because the invader's impact is, in part, a function of its density (Parker *et al.* 1999; Sofaer *et al.* 2018). However, widespread application of this logic to any alien species classified as "invasive" in any recipient ecosystem ignores the context sensitivity of the invasiveness–impact relationship (Barney *et al.* 2013; Essl *et al.* 2017), and does not account for per capita effects (Spencer *et al.* 2016; Dick *et al.* 2017; Pearse *et al.* 2019). Assuming that a species invasion affects multiple systems in the same way may oversimply the invasiveness–impact relationship and create false impressions of certainty (Johnson and Lidström 2018). In invasion science and policy, complexities and uncertainties must be explicitly and clearly understood and acknowledged – that is, the strength and confidence (in the statistical sense; that is, with respect to explanatory power and the variability/error in correlations) of surrogate–impact relationships should be evaluated and validated in a rigorous and systematic way. And yet such assessments are rare.

We discuss how the use of ecological surrogacy to infer unmeasured ecological impacts of invasive species is often overlooked in invasion science. This is not a critique of the many approaches for measuring ecological impact directly (eg Vilà *et al.* 2018) but rather a discussion of how surrogate measurements are used after a direct assessment is completed (or are used in place of a direct assessment) to infer impacts that remain unmeasured. We consider how both researchers and managers often justify the widespread application of a variety of surrogate–impact models based on limited, context-specific evidence of impacts involving a small number of invasive species. For simplicity, we restrict our discussion (for the most part) to ecological impacts, although we recognize that these surrogate measures may also be used to infer socioeconomic impacts, which are also important (Jeschke *et al.* 2014; Bacher *et al.* 2018). We also detail how greater integration of existing surrogate frameworks into invasion research and management offers a previously unrecognized solution to issues related to quantifying, demonstrating, managing, and communicating the ecological impacts of invasive species.

Surrogate–impact models used in invasion research and management

Using a surrogate is a practical solution for collecting meaningful information about a target of interest in cases where measuring that target directly or completely is too difficult as a result of financial, temporal, or logistical constraints (Lindenmayer *et al.* 2015; O'Loughlin *et al.* 2018). Surrogates are used in ecology to provide information about ecosystems ("indicator surrogates") and/or as tools to facilitate management intervention ("management surrogates") (Hunter *et al.* 2016). These two approaches are often complementary; for example, monitoring beaver abundance (*Castor canadensis* and *Castor fiber*) can act as an indicator surrogate by providing information on habitat availability for pond-dependent biota, and as a management surrogate by revealing whether management intervention to conserve beavers (eg predator control) has been successful (Hunter *et al.* 2016). Both forms of surrogacy are essential to invasion ecology, where the status of an invader can inform the most common research and management goals of (1) understanding the ecological impacts caused by invasive species (ie an indicator surrogate) and (2) effectively controlling those species as a means of conserving and enhancing native ecosystems (ie a management surrogate) (Courchamp *et al.* 2017).

Invasion itself can be conceptualized as two linked yet distinct components: the *determinants* and the *consequences* of invasion success. The combination of factors that facilitate invasion success have been thoroughly studied, leading to an array of proposed hypotheses that explain progress along the invasion pathway, and a detailed understanding of how measures of propagule pressure, species traits, and properties of recipient ecosystems can be used as surrogates to infer invasion success (Figure 1; Lockwood *et al.* 2005; Catford *et al.* 2009; Blackburn *et al.* 2011). As such, the use of surrogates to measure invasion success will not be detailed here. Conversely, the ecological consequences of invasions have been examined to a far lesser extent. The few hypotheses underpinning species impacts are not well supported by data, and confidence is lower in how measures of the invasiveness of a given species may act as surrogates for ecological impacts (Hulme *et al.* 2013; Essl *et al.* 2017). However, surrogates for impacts are widely used to identify which invasions will likely have the most severe ecological consequences and should be prioritized for management (Kumschick *et al.* 2012; Prior *et al.* 2018). In the sections below, we detail four key surrogate–impact relationships that underpin invasion research and guide invasive species management (Figure 1).

(1) Invader presence as a surrogate for impact

The presence of an invasive species is probably the simplest surrogate for impact used in both research and management (Figure 1, relationship 1), and is commonly employed where collecting robust data on local abundance or geographic extent may be prohibitive (eg a cryptic invader; Jarić *et al.* 2019). Using the presence of a species to infer its impact presupposes either (1) that impact is a fundamental characteristic of any alien species classified as "invasive" (Blackburn *et al.* 2014), and/or (2) that well-documented invasion–impact relationships can be extrapolated to invasive

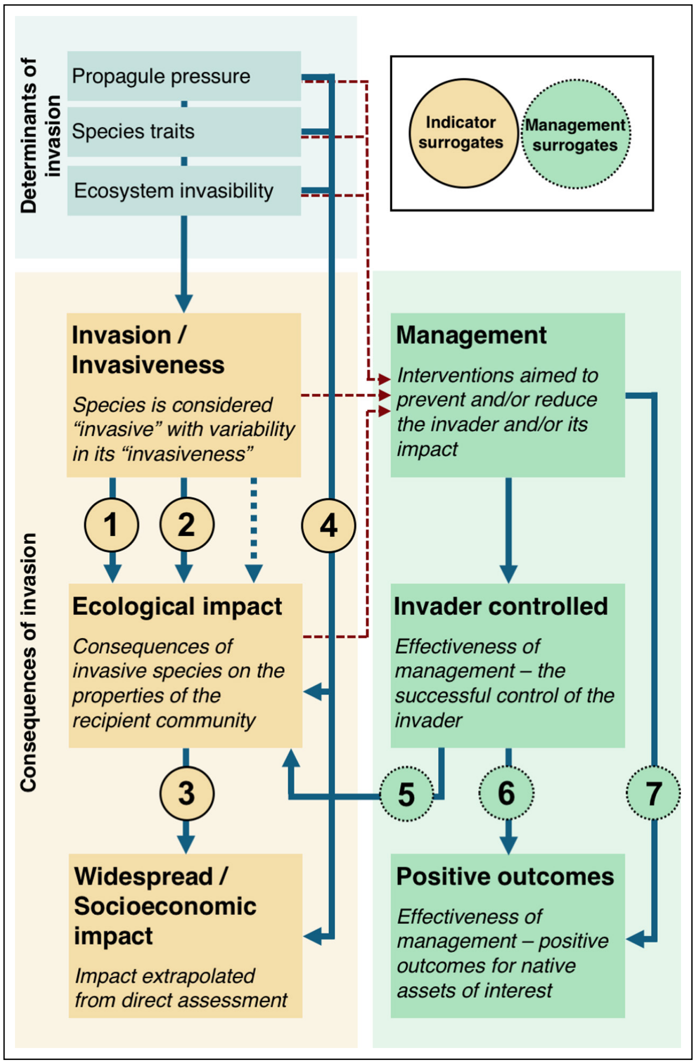

Figure 1. The surrogate models widely used in research and management to infer the determinants and consequences of species invasion. Arrows linking concepts reflect where measures of one are used to infer the other. Numbers refer to the surrogate–impact relationships that are either "indicator surrogates" ([1] presence is a surrogate for impact; [2] invasiveness is a surrogate for impact; [3] some impact is a surrogate for widespread impact; and [4] determinants of invasion are surrogates for consequences of invasion [ie ecological impact]) or "management surrogates" ([5] invader removal is a surrogate for removal of impacts; [6] invader removal is a surrogate for positive ecosystem outcomes; and [7] management intervention is a surrogate for positive ecosystem outcomes). Dashed red arrows reflect how measures of a species invasion are used to trigger invasive species management; dashed blue arrow reflects that there are other measures of a species "invasiveness" that we have not specifically detailed in the main text (eg geographic extent).

species whose impacts have not been measured (Barney *et al.* 2013; Nentwig *et al.* 2016). For example, this impact surrogate is often broadly applied to invasive plants, and justified by meta-analyses of published data that consistently reach the conclusion that invasive plants have negative effects on native communities (Figure 2a; Pyšek *et al.* 2012). However, these analyses are likely skewed by publication bias toward species, metrics, and conditions where the most substantial impacts would be expected (Didham *et al.* 2005; Guerin *et al.* 2018). Similarly, such analyses usually compare invaded and non-invaded areas but do not identify the threshold of invasion where impact would begin (Panetta and Gooden 2017). The evidence that supports presence as a robust surrogate for impact is often context dependent, and ignoring that context risks misrepresenting threats. Although presence–impact is a robust relationship for those highest-impact invaders (often referred to as "transformers" rather than "invasives"; Richardson *et al.* 2000), the presence of other invasive plants, for example, is just as likely to have neutral or positive ecosystem effects (Seabloom *et al.* 2013; Pearson *et al.* 2016).

(2) Invasiveness as a surrogate for impact

Measures of a species' invasiveness are widely considered to be an informative indicator of impact (Figure 1, relationship 2; Essl *et al.* 2017). There are multiple dimensions that contribute to the overall invasiveness of a species, including environmental range, geographic extent, rate of spread, and local abundance and density (Catford *et al.* 2016), all of which may relate to a species' impact. Density or abundance is probably the most common dimension of invasiveness used to infer impact, and is a relationship largely supported in individual studies (Parker *et al.* 1999; Barney *et al.* 2013). For example, Gooden *et al.* (2009) found considerable evidence of linear and non-linear impacts of increasing cover of an invasive shrub on native vegetation, suggesting invader abundance strongly represented its ecological effects (Figure 2b). However, it is well established that impact is also a function of per capita effects, which in turn are mediated by environmental factors independent of the invader; as such, invasiveness should not be expected to be a consistent surrogate for impact across time and space (Dick *et al.* 2017; O'Loughlin and Green 2017b; Sofaer *et al.* 2018). For instance, the only cross-taxonomic meta-analysis of the invasiveness–impact relationship (where rate of spread and establishment of the invader were the dimensions of invasiveness considered) found no consistent correlation in any biotic group (Ricciardi and Cohen 2007), and other reviews focusing on invasive plants have not considered this relationship, citing insufficient data (Pyšek *et al.* 2012; Catford *et al.* 2016). Despite the findings of these syntheses, the application of this surrogate (ie some dimension of invasiveness) in research and management is often justified by existing evidence of impact by the invader at some time and in some contexts (Kulhanek *et al.* 2011).

(3) Some impact as a surrogate for widespread impact

Measures of impact on some components of the recipient community in some contexts are often used to infer more widespread consequences of invasive species (Figure 1,

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Figure 2. Examples of species and contexts in which surrogate measures are often used to infer unmeasured ecological impacts: (a) in a deciduous forest ecosystem, the presence of invasive Japanese stiltgrass (*Microstegium vimineum*) is used to infer decreased native plant diversity, as invasive plants in general are known to have that effect; (b) the density of the invasive shrub lantana (*Lantana camara*) is used to infer loss of native species due to established invasiveness–impact relationships and impact thresholds; (c) the ecological impacts of similar birds are used to infer those of the great kiskadee (*Pitangus sulphuratus*); and (d) niche models that predict the abundance of invasive common carp (*Cyprinus carpio*) are used to infer well-known water-quality effects of this benthic feeder.

relationship 3). This use of ecological surrogacy draws notable parallels to how surrogates are commonly applied in biodiversity monitoring, where particular taxa are monitored to provide information on a collection of unmeasured groups: that is, measuring a *part* to make inferences about the *whole* (Barton *et al.* 2015; Lindenmayer *et al.* 2015; Westgate *et al.* 2017). It also underpins the semi-quantitative categorical approach of classifying invasive species based on the magnitude of their largest demonstrated effect (eg as causing "minor", "moderate", or "major" impacts) that are becoming common in invasion science (Kumschick *et al.* 2012; Blackburn *et al.* 2014). Although it has been claimed that these classifications are based on adequate evidence, the contextual details of that evidence are generally ignored in subsequent research that considers the impact classification as a fixed and generalizable property of the species (Doherty *et al.* 2016; Evans *et al.* 2018). However, research on the impacts of invasive species is plagued by inconsistent methodology, and is largely restricted to snapshot studies that consider few response variables (Hulme *et al.* 2013). For example, two-thirds of invasive bird species that have been identified as having any impact were classified using evidence considered of "low–medium" confidence, meaning that all or some of the data are poor, difficult to interpret, and indirect (eg data are from another similar species) (Figure 2c; Evans *et al.* 2016). Using quantified impacts of a few metrics as surrogates for a broader impact assessment greatly underrepresents the variability of ecosystem effects that any species can have, which can be captured through the consistent testing of a larger variety of metrics (Barney *et al.* 2013).

(4) Determinants of invasion as surrogates for consequences of invasion

Assuming that invasion and invasiveness are strong predictors of invader impact, it stands to reason that the determinants of invasion can, in turn, act as surrogates for the consequences of invasion (Figure 1, relationship 4). This application essentially uses indirect measures of impact, meaning the measure is conceptually farther from the target than the other surrogate–impact relationships discussed above. Two or more links between

Panel 1. Using an adaptive surrogacy framework to select and evaluate surrogates for impact

An adaptive surrogacy framework (Lindenmayer *et al.* 2015) treats proposed surrogates as working hypotheses to be subjected to rigorous testing. Although undertaking invasive species monitoring may not always be hypothesis driven (eg monitoring occurs for political, social, or economic motivations; Courchamp *et al.* 2017), using other measures to infer unmeasured ecological impact clearly represents a testable prediction based on assumptions and prior knowledge. Applying an adaptive framework to select and evaluate surrogates of ecological impact would make management practices more objective and remove bias from many of the ways invasive species are identified and prioritized for management across the globe. The key considerations of the framework in an invasion ecology context are detailed below.

Identification of surrogates

Potential surrogates

Consider all measurable qualities of a species invasion that could influence impact; they can include the presence of a species, some dimension of its invasiveness (eg local abundance), species traits and environmental context, and some aspect of the ecosystem that is likely to be impacted.

Benchmarks and triggers

It is important to establish clear reference points and baselines to assist later interpretation of the surrogate–target relationship; this consideration is critical for determining where ecosystem change relates to invader impacts or other influencing factors and natural variation, and ideally involves thorough understanding of the invaded ecosystem, time-series monitoring, and control reference states.

Sampling approach

The methodology used to quantify a surrogate can greatly influence its accuracy and usefulness for representing impact; surrogate–impact relationships assessed at a particular spatial or temporal scale may not be transferable to a different spatial or temporal context. For instance, quantifying density effects of an invasive plant at a plot scale may not accurately represent impact at a site or landscape scale.

Evaluation of surrogates

Scientific validity

This is the critical step of quantifying the accuracy, certainty, and stability of the surrogate–impact relationship to be used. Although any surrogate for impact will be imperfect, it is important to quantify uncertainty and the level of confidence in the inferences being made. As such, the spatial and temporal boundaries under which the surrogate is robust and valid should be made clear.

Cost effectiveness

The monetary costs and benefits associated with invasive species monitoring, impact assessment, and surrogate identification and evaluation are not trivial and need to be considered. The most accurate surrogate for impact is unlikely to be monitored if it is very expensive to do so, whereas the most cost-effective surrogate may not be robust enough to confidently indicate impact and may instead be highly influenced by confounding factors.

Risk assessment

Consider and compare the range of possible ecosystem outcomes that may occur from either under- or overestimating ecological impact, and making decisions based on the "wrong" surrogate. For example, overestimating the impact of a species risks the misallocation of limited resources, whereas underestimating impact could have severe ecological consequences.

surrogate and target create more opportunity for variation and error, meaning any inferences made will be inherently less accurate (Lindenmayer *et al.* 2015; Westgate *et al.* 2017). Although the determinants and consequences of invasion are largely considered to be independent of each other (Courchamp *et al.* 2017; Ricciardi *et al.* 2017), determinants of invasion, such as species traits and environmental context, are ultimately the most highly sought after by both researchers and practitioners to predict ecological consequences. For instance, niche-based modeling uses information on species traits and environmental tolerances to predict occurrence and abundance (ie invasion success), which are then used to infer impacts (Kulhanek *et al.* 2011). One study that employed this approach to predict invasive common carp (*Cyprinus carpio*) impacts recognized that predicted abundance was being used as a surrogate for impact (Kulhanek *et al.* 2011) but did not acknowledge that the niche model itself was using a surrogate for abundance, or that the contemporary ecosystem impacts of carp may be more nuanced (eg Kopf *et al.* 2017) than simply the long-established effects on water quality that the authors cited (Figure 2d). Similarly, for invasive birds, identifying specific traits that strongly predict impact may work in some instances (eg predatory birds that have major effects on native prey), but overall it is widely distributed generalist species that have the most severe (and diverse) impacts (Evans *et al.* 2018). The assumed strong links that justify using determinants of invasion as surrogates for impact are largely unsupported because the processes that determine invasion success are rarely the same as those that drive impact (Essl *et al.* 2017).

Why the use of impact surrogates requires evaluation

The use of surrogates is a practical means of facilitating evidence-based assessments where financial, temporal, or logistical constraints may limit collection of the most representative data (Lindenmayer *et al.* 2015; O'Loughlin *et al.* 2018). Surrogates are widely used to infer difficult-to-measure invasive species impacts for two key reasons. First, it is considered appropriate to assume that an invasive species will have severe ecological consequences so as to prioritize their management and avoid major impacts. Second, there are often practical constraints and ethical considerations that limit the ability of researchers and managers to quantitatively determine impacts in robust ways. Both approaches are motivated by the "precautionary principle", in that it is better to assume there will be negative impacts and act quickly than to wait for strong evidence and potentially risk irreversible change (Hulme *et al.* 2013). However, there are also potential risks associated with failing to evaluate the accuracy, stability, and certainty of surrogate–target relationships on a regular basis (Panel 1; Lindenmayer *et al.* 2015; Barton *et al.* 2015; Hunter *et al.* 2016).

Inferences derived from surrogate measurements involve unavoidable uncertainty, meaning there is a risk that the inference being made is wrong (O'Loughlin *et al.* 2018). The ways surrogates are currently used to infer ecological impacts of invasive species (Figure 1) represent practical decisions to measure something that is more generalizable, cost-effective, and communicable over something with greater accuracy, certainty, and robustness (ie the direct quantification of ecosystem effects; Lindenmayer *et al.* 2015). For instance, invasive mammalian predators are considered particularly damaging to native biodiversity, and have been implicated in the majority of documented vertebrate extinctions globally (Doherty *et al.* 2016). Using a more easily measured surrogate (eg presence or abundance of the predator) to infer population-level effects on native prey species is then justified given the potential for impact, limited conservation funding, and the need to communicate the issue to a broad and diverse audience (Courchamp *et al.* 2017). However, in a particular context, native prey populations may be far more responsive to habitat availability, disturbance history, or interspecific competition than an invasive predator (Zavaleta *et al.* 2001; Hradsky *et al.* 2017). For example, Hradsky *et al.* (2017) found that the relationship between invasive red fox (*Vulpes vulpes*) abundance and impact on native prey species was greatly influenced by fire and vegetation structure, suggesting measures of fox activity alone were poor surrogates for impact (Figure 3a). Simple and generalizable surrogates for biodiversity also show low consistency when context is considered (Westgate *et al.* 2017), highlighting that simple impact surrogates also may not be particularly robust.

Many researchers caution against using poorly assessed surrogate relationships to reach important conclusions and make decisions, given the high likelihood of chance correlation or context-dependency between a surrogate and target (Westgate *et al.* 2017; O'Loughlin *et al.* 2018). Similarly, high invasiveness of a species may merely reflect an altered or degraded community where the invader is a passenger and not a driver of change (Didham *et al.* 2005). For instance, the invasive giant African land snail (*Achatina fulica*) establishes and spreads within the rainforests on Christmas Island only after that ecosystem has been altered by other invasive taxa (O'Loughlin and Green 2017b), and high densities of the snail do not have the measurable impacts on seedling recruitment or leaf litter dynamics that would be expected based on the snail's known traits and behaviors observed elsewhere (Figure 3b; O'Loughlin and Green 2017a). Therefore, any measure of this species' presence, abundance, functional traits, or impacts in a different setting would misrepresent the ecological impacts of this invasion.

The improved application of surrogates for impacts requires the adoption of a robust framework in which identified surrogates are explicitly evaluated for their scientific validity (see Panel 1). For example, Lindenmayer *et al.* (2015) developed an "adaptive surrogacy framework" that aims to unify surrogate concepts across disciplines and applications. Their framework is a guide to whether a surrogacy or direct measure approach is most effective in providing accurate information while also being cost-effective and

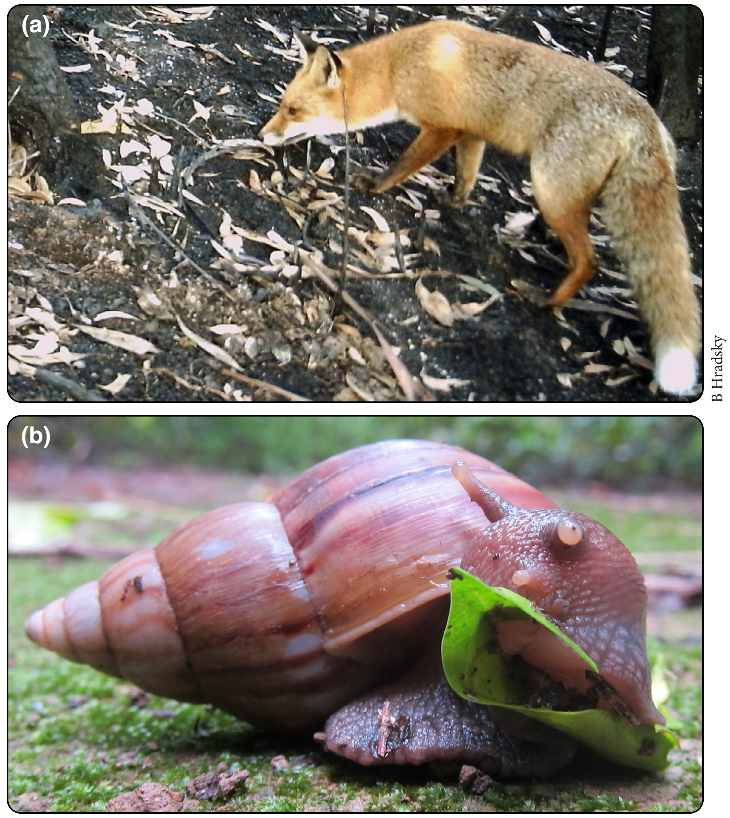

Figure 3. Examples of species for which the context of their invasion is critically important to understanding and inferring their ecological impacts. (a) Although invasive red foxes (*Vulpes vulpes*) have substantial impacts on native prey, often the magnitude of those impacts is mediated by disturbance and vegetation attributes (eg Hradsky *et al.* 2017), and as such red fox abundance alone may not be the most robust surrogate for impact. (b) The giant African land snail (*Achatina fulica*) is a problematic species throughout the tropics, yet on Christmas Island it is largely inhibited from establishing in rainforests and has limited impact when it does (O'Loughlin and Green 2017a), indicating that information about this species collected elsewhere was not a robust surrogate for its impacts on Christmas Island.

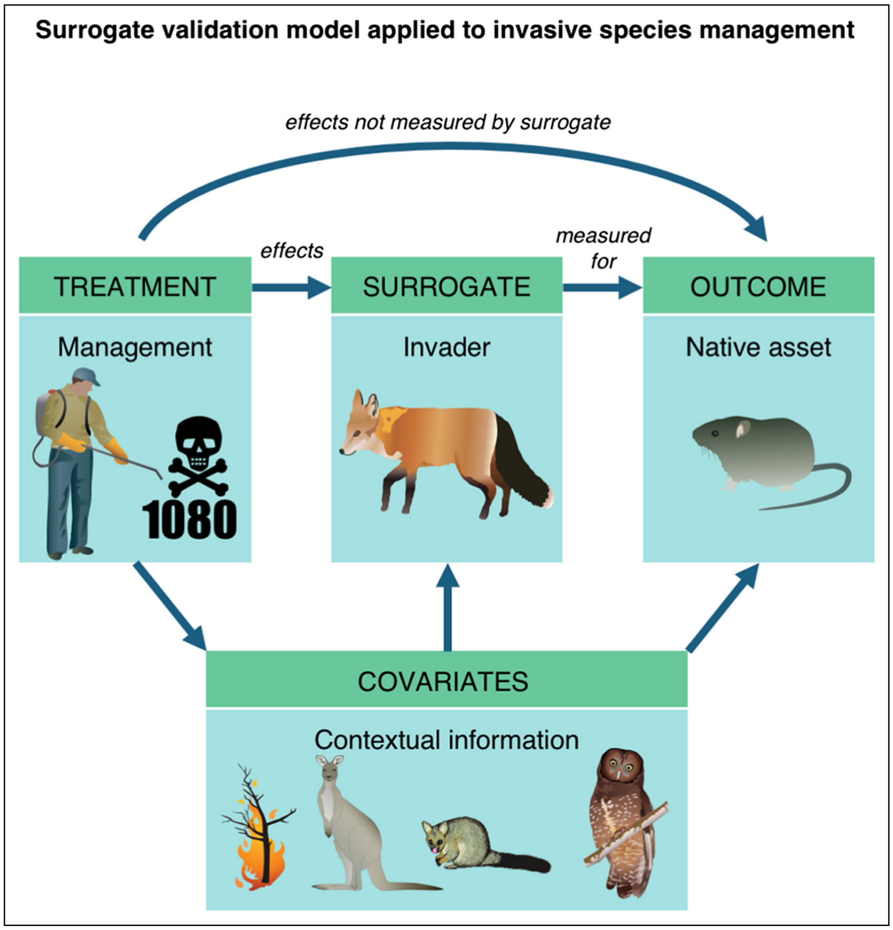

Figure 4. Framework for surrogate validation and its application in an invasive species management context. Conceptual model relates a treatment effect to a specified outcome via a surrogate (Panel 2). For invasive species management, measures of invasive species response to control efforts (ie management efficacy) are regularly used to infer positive ecosystem outcomes of that control. For example, the number of poison baiting stations deployed (treatment) is used to decrease the abundance of invasive predators (surrogate) in order to increase the population size of native prey species (outcome). There may also be direct (non-target) effects of the treatment on the outcome (eg number of prey species killed from poison baiting) and those effects may not be captured by measuring the surrogate. Abiotic drivers, competition, and native predators can influence the surrogate–outcome relationship (covariates) (Lindenmayer *et al.* 2018). Vector images are courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (www.ian.umces.edu/symbols; used with permission).

easily communicated in a particular context (Panel 1). The key benefit to adopting this four-part hypothesis-driven framework in invasion science is that it provides researchers and managers with a tool to more clearly recognize their use of surrogates, to justify using them, and to avoid undue criticism when making inferences about impacts. Part 1 of the framework involves determining a clear target (that is specific, measurable, attainable, relevant, and time-bound), engaging with stakeholders to capitalize on diverse experiences and expertise, and developing a conceptual model of the target system to ensure links between potential surrogates and targets are logical; Parts 2 and 3 involve the identification and evaluation of surrogates, respectively (detailed in Panel 1); and Part 4 involves selecting and implementing a surrogate, and using active learning to identify key sources of uncertainty and continually improve the inferences being made. Greater integration of these kinds of lessons from surrogate ecology into invasion science offers a previously unrecognized solution to issues related to quantifying, demonstrating, managing, and communicating the ecological impacts of invasive species.

Validating control of invasive species as a management surrogate

The broad goals of conservation management are to control threats, and protect and enhance native ecosystem values. Therefore, considerable resources are dedicated to invasive species management programs under the premise that effective removal of an invasive species (a surrogate) corresponds to a reduction in a threat and some improvement to the invaded ecosystem (Figure 1, relationships 5 and 6, respectively) (Reid *et al.* 2009; Panetta *et al.* 2019). This approach reflects a conservation practitioner or manager applying the previously discussed surrogate–impact relationships to their program, and takes an additional step in logic by asserting that if invasion infers ecological impact, then removal of the invader removes the impact. Although that interpretation may seem overly simplified, in practice the link between invasiveness and impact is rarely evaluated before management is undertaken, and management effectiveness is typically determined only by observing the response of the invader and not broader ecosystem outcomes (Kettenring and Adams 2011; Doherty and Ritchie 2017; Prior *et al.* 2018). Similarly, when ecosystem recovery *is* measured following invasive species management, negative and mixed outcomes are almost as common as positive ones (Prior *et al.* 2018). The use of an invasive species' response to management or management itself (Figure 1, relationship 7) as a surrogate for benefits to the managed ecosystem may be greatly limited in instances where the link between invasiveness and impact was not first clearly determined.

There are many contrasting cases where successful management of an invader was or was not a good surrogate for positive ecosystem outcomes. For example, the eradication of invasive mammals from islands improves seabird nesting success and adult survival (Brooke *et al.* 2017), meaning the response of

Panel 2. Using causal frameworks to validate impact surrogates in response to management

Causal frameworks examine the links between treatments and their effects, and how well surrogates can predict those effects (Figure 4; Barton *et al.* 2015). Whereas the presence and abundance of an invasive species may be a robust indicator of ecological impact, the removal of an invader through management intervention *may not* automatically indicate the removal of or recovery from those impacts. As such, the most accurate surrogate to infer ecological impact of an invader is unlikely to be the same surrogate that best represents ecological outcomes of management. This framework for surrogate validation should be used in combination with the adaptive framework for surrogate selection and evaluation (see Panel 1) to ensure the accuracy of inferred impacts of both invasive species and their management.

Surrogacy frameworks are toolkits for assessing the validity of claims with regard to invasive species impacts and management. For instance, invasive predators are frequently targeted for widespread control to protect native prey, yet the efficacy of this practice is rarely considered (see next paragraph for an example) (Doherty and Ritchie 2017). Therefore, when deciding whether to implement control actions and/or the reported outcomes of those actions, it is important to ask (1) How have predator impacts on native species and ecosystems been determined (ie what is the impact surrogate)? (2) How much evidence supports the assessment of impact (ie how robust is the impact surrogate)? (3) Have spatial and temporal covariates and environmental context been accounted for (ie how stable is the impact surrogate)? (4) Has management reduced predator impacts, not merely reduced predator numbers (ie how responsive is the impact surrogate)? and (5) How have positive biodiversity and ecosystem outcomes been shown to respond to management (ie how accurate is the impact surrogate)? The level of objectivity in the assessment of a species impact and the degree in which management action is evidence-based will become apparent by asking these questions of any program, and by explicitly considering the use of ecological surrogacy intrinsic to each of them.

For example, a poison baiting program to control invasive red fox (*Vulpes vulpes*) in an iconic Australian reserve was successful in terms of removing the invader, but unsuccessful in terms of having positive outcomes for native mammal fauna (Figure 4; Lindenmayer *et al.* 2018). Native mammals declined and some species became locally extinct over the 15 years following intense fox control (Figure 4). In this case (Lindenmayer *et al.* 2018), despite the treatment (baiting) having a major effect on the surrogate (fox numbers), the surrogate was not representative of the desired outcome (benefits to native prey).

the invader to management is a strong indicator of a change in a threat (predation pressure) and positive outcomes for biodiversity (recovery of the impacted bird community). Conversely, removal of invasive plants more frequently leads to the establishment of other invaders, and cleared sites may show no evidence of return to the target native community even decades after removal, due to invader legacy effects and landscape disturbances (Maclean *et al.* 2018; Panetta *et al.* 2019). Similarly, native prey assemblages may collapse after the successful eradication of an invasive predator without any clear reason why (Lindenmayer *et al.* 2018). In those cases, information about the response of the invader to management alone is not an informative surrogate for either of the two broad goals of management (ie invader threat is not clear, and removal did not result in ecosystem recovery).

Ultimately, practitioners prioritize the management of invasive species based on the belief that those species are having severe ecological impacts, and for the most part lack the resources and capacity to test that assumption (Kuebbing and Simberloff 2015). However, failure to quantify the impacts of a species risks wasting limited resources on managing species that are not necessarily the most problematic, potentially leading to undesirable outcomes for the native ecosystem (Barney *et al.* 2013; Kopf *et al.* 2017). For instance, attempts to eradicate invasive cordgrass (*Spartina* spp) in California salt marshes led to population declines of endangered rails (*Rallus* spp) that were relying on cordgrass for nesting and foraging habitat (Lampert *et al.* 2014). These kinds of positive effects of invaders will be increasingly important for biodiversity in more modified ecosystems, and should be key considerations for scientists, managers, and decision makers prior to embarking on large-scale control programs (Kopf *et al.* 2017). Whether or not the response of the invader to management action will be a robust surrogate for positive ecosystem outcomes will depend on the strength of the relationships between management treatment, surrogate measure, and conservation target, and how explicitly they are validated (Figure 4; Panel 2; Barton *et al.* 2015).

Conclusions

The threats posed by invasive species are underappreciated (Ricciardi and Ryan 2018); the frameworks and tools employed to assess invader impacts therefore need to be explicit and robust enough to limit misrepresentation and the risk of ineffective management (Courchamp *et al.* 2017). Possible solutions for improving impact assessments include (1) formally recognizing that ecological surrogacy is being implicitly used in invasive species research and management, and (2) applying quantitative approaches, used to evaluate and validate surrogate–target relationships in other fields, to surrogates of invasive species impacts. Surrogates are only as strong as the assumptions on which they are based, and support for many long-held assumptions in invasion ecology is declining (Jeschke *et al.* 2012). Inferring "impact" from "invasiveness" is a logical assumption, but an assumption nonetheless; therefore, it seems obvious that the accuracy, stability, and certainty of the surrogate–impact relationships that are widely used in invasion science would need to be rigorously and regularly tested. Current approaches for assessing the ecological impacts of invaders may downplay the uncertainty in measures and embrace a generalizable classification (eg Blackburn *et al.* 2014), advocate for greater direct quantitative assessments to improve accuracy (eg Barney *et al.* 2013), or strongly encourage more explicit measures of a species' per capita effects (eg Dick *et al.* 2017). For example, recent use of the "relative impact potential" metric (Dick *et al.* 2017) makes it clear that the measures like abundance and life span were being used as surrogates to infer population response (Dickey *et al.* 2018). This is an important step forward, and we suggest that greater appreciation of the frameworks already developed for assessing biodiversity surrogates (Lindenmayer *et al.* 2015) will further improve certainty around inferences of invader impacts through increased empirical quantification.

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