Two roles for ecological surrogacy: indicator surrogates and management surrogates

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Keywords: coarse-filter, environmental management, flagship species, focal species, indicators, monitoring, environmental proxy, surrogates, terminology, umbrella species.

Word count: 5052

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Abstract: Ecological surrogacy—here defined as using a process or element (e.g., species, ecosystem, or abiotic factor) to represent another aspect of an ecological system—is a widely used concept, but many applications of the surrogate concept have been controversial. We argue that some of this controversy reflects differences among users with different goals, a distinction that can be crystalized by recognizing two basic types of surrogate. First, many ecologists and natural resource managers measure "indicator surrogates" to provide information about ecological systems. Second, and often overlooked, are "management surrogates" (e.g., umbrella species) that are primarily used to facilitate achieving management goals, especially broad goals

such as “maintain biodiversity” or “increase ecosystem resilience.” We propose that distinguishing these two overarching roles for surrogacy may facilitate better communication about project goals. This is critical when evaluating the usefulness of different surrogates, especially where a potential surrogate might be useful in one role but not another. Our classification for ecological surrogacy applies to species, ecosystems, ecological processes, abiotic factors, and genetics, and thus can provide coherence across a broad range of uses.

Introduction

In October 2014 a diverse group of scientists from around the world gathered in Australia to spend three days exploring the full scope of ecological surrogacy, primarily trying to achieve a broad, synthetic understanding that would advance the use of this important concept. They ranged from conservation practitioners and scientists who use bacteria and lichens to monitor pollution, to those who try to foster ecological integrity of whole oceans, or try to conserve regional biodiversity by managing representative arrays of ecosystems. The participants soon discovered that, despite a common interest in the use of surrogates for monitoring and managing ecological systems, they did not share a foundational understanding of ecological surrogacy. In particular, those who measure surrogates as ecological indicators found it difficult to embrace the concept of surrogates as alternative foci for management. For example, managing an umbrella species because it is an efficient way to maintain a large set of species did not seem like a form of surrogacy to them, whereas this was a key form of surrogacy for others. This led to many hours of discussion and ultimately we reached a consensus that explicitly recognizes two basic forms of surrogates based on goals: indicator surrogates (which are measured to provide information about ecological systems) and management surrogates (which are managed to achieve a different, often larger, goal such as “maintain biodiversity”). In this paper, we argue that this dichotomy represents a meaningful division in how different groups use ecological surrogacy. We discuss why this schism has emerged, and give examples of how it applies to five types of ecological components: species, ecosystems, ecological processes, abiotic factors, and genetics. We argue that disagreements over surrogate utility typically occur between groups with different goals, and that by explicitly recognizing two overarching goals for ecological surrogacy--providing information about ecological systems and facilitating their management--future misunderstandings can be avoided.

Context and Definitions

Although ecological surrogacy is a frequently used concept (nearly 50,000 journal articles by one count; Westgate et al. 2014), it has repeatedly defied simple classification. For example, the United Nations (UNCDD 2013), Secretariat of the Convention on Biological Diversity (2014), European Union (BISE 2014), Australia's State of the Environment Program (ANZECC State of the Environment Reporting Task Force 2000), and the United States Fish and Wildlife Service (USFWS 2014) have all embraced different uses of surrogates. This lack of consensus amongst academics and practitioners on a shared terminology or scheme of classification remains despite repeated critiques and attempts at standardization (e.g., Landres et al. 1988; Noss 1990; McGeoch 1998; Simberloff 1998; Dale & Beyeler 2001; Niemi & McDonald 2004; Caro 2010; Heink & Kowarik 2010; Pereira et al. 2013; Lindenmayer et al. 2015; Stephens et al. 2015). We propose to build a simple foundation for ecological surrogacy by recognizing that many seemingly distinct applications of the surrogate concept share common goals: environmental monitoring or informing management. Our focus on goals differs from earlier classification schemes that emphasized differences among organizational scales (e.g., genes, species, or ecosystems; Caro 2010, Table 1), ecological attributes (e.g., compositional, functional, or structural; Noss 1990), or distinct types of problem (e.g., environment, ecology, or biodiversity surrogates; McGeogh 1998).

We begin with a definition of ecological surrogacy to distinguish it from surrogacy in medicine, engineering, and other fields (Forrester et al. 2008, Barton et al. 2015):

Ecological surrogate: An ecological process or element (e.g., species, ecosystem, or abiotic factor) that is used to represent (i.e., serve as a proxy for) another aspect of an ecological system.

The earliest explicit uses of surrogates focused on measuring one species as an indicator for others: i.e., beginning in 1893, the concentration of *Escherichia coli* was used to indicate the likely presence of other pathogens in drinking water (Ashbolt et al. 2001). This usage is clearly consistent with our definition of indicator surrogates:

Indicator surrogate: A type of surrogate that provides information about another aspect of an ecological system: for example, measuring the population density of species A because it provides information about the condition of target ecosystem X.

This approach emphasizes a mechanistic, statistical approach to surrogacy that remains popular amongst environmental scientists. However, a dramatic expansion in the use of the surrogacy concept in ecology and conservation biology arose alongside the development of the concept of "biodiversity" in the 1980s. Advocates of maintaining biodiversity realized that it was impractical to address directly all of the elements of biodiversity given the vast numbers of species, especially little-known or undescribed invertebrates and microbes, or the genetic components of biodiversity. Thus, conservation practitioners needed surrogates that could be readily managed under the assumption that managing the surrogate would be beneficial for a sizable portion of biodiversity. (In this paper we use "management" broadly to cover activities as diverse as controlling a contaminant, conserving a game species or endangered species, planning a reserve system, or motivating public support for conservation.) From this emerged the idea of a conservation "umbrella" in which one species is used to represent biodiversity for management purposes (Frankel & Soule 1981). Similarly, but on an ecosystem level, "coarse-filter" conservation assumed that protecting a representative array of ecosystems would encompass much biodiversity at the species and even genetic levels, with relatively few species falling through the filter's pores unprotected (Noss 1987). With both umbrella species and coarse filters, the primary goal is to manage X to achieve the real target goal Y. In addition to biodiversity, other broad conceptual entities such as ecological integrity (Rapport et al. 1998) or resilience (Walker & Salt 2012) have also become the basis for setting large goals that are often addressed using proxies that we call "management surrogates."

<u>Management surrogate:</u> *A type of surrogate that is a tool for management because it represents another aspect of an ecological system that is the main goal of management: for example, managing the population of species A because this facilitates maintaining the integrity of ecosystem X.*

Therefore, management surrogacy focuses primarily on facilitating management of ecological systems whereas indicator surrogacy focuses primarily on providing information about those systems.

We suggest that our binary, goal-oriented approach to surrogate classification represents an improvement over existing schemes for two reasons. First, our conceptual understanding of how to classify ecological systems is diverse and evolving, but goals of measuring and managing ecosystems are relatively constant. Second, scientists often do not articulate clear, explicit goals, and so discussion about goal setting is likely to be beneficial to the science and application of surrogates.

The definitions provided above are distinct, but when surrogates are applied in practice there can easily be overlap; we turn to this issue next.

Divergent goals and surrogate effectiveness

When management surrogates and indicator surrogates are seen as complementary constructs, some past debates over surrogate effectiveness can be reinterpreted as differences between users with different goals and approaches (Caro 2010). For example, controversies over the utility of focal species (Lambeck 1997, Lindenmayer et al. 2002) or flagship species (Simberloff 1998) may have arisen because management surrogates were incorrectly interpreted as indicator surrogates.

To illuminate the distinctions and overlaps between management and indicator surrogates, we offer three well-known examples. First, we consider an example in which a species might be an effective management surrogate for biodiversity even though it would probably be an ineffective indicator surrogate of biodiversity. Tigers (*Panthera tigris*) are difficult to count and select habitat at coarser scales than most species, and thus are an ineffective indicator surrogate. Yet organizing biodiversity management around tigers as an umbrella species may be sensible because conserving their habitat (mangrove swamps to boreal forests) would provide habitat for thousands of other species (Wikramanayake et al. 2008). A converse example (an effective indicator surrogate that is an insufficient management surrogate) may be found with *E. coli*. Monitoring *E. coli* may indicate if rivers are free of fecal contamination, but in many rivers, the key to restoring ecological integrity is fostering natural river flows (e.g., removing in-stream barriers and managing flow through dams, Beechie et al. 2010). In this case, an ecological process, the flow regime, would be a more effective management surrogate. These two examples are clearcut, but when surrogates are applied in practice there is often substantial overlap between management and indicator surrogacy. Consider the role of beavers (*Castor canadensis* and *C. fiber*) in providing habitat for pond-dependent biota. If we monitor beaver populations with the goal of assessing and tracking habitat availability for other species such as waterfowl, beavers are serving as an *indicator surrogate*. If we increase the beaver population, perhaps by banning trapping, with the goal of increasing the number of beaver dams and thus ponds, this is *management surrogacy*. In many cases, these approaches will be coordinated and thus both forms of surrogacy used, but this is not necessarily the case. One could manage beavers to increase the number of beaver ponds without systematically monitoring their populations. Alternatively, one could monitor beavers to indicate changes in other pond-dwelling species, without any active beaver management.

Surrogacy in five classes of ecological components

To demonstrate how our definitions relate to surrogate use in practice, we apply the "indicator surrogates" and "management surrogates" concept to five classes of ecological components: species, ecosystems, ecological processes, abiotic factors, and genetics. We selected these to show the wide applicability of our concept, not to imply that they are the basis of a robust classification (e.g., one could readily combine ecosystem processes and ecosystems or split abiotic factors into physical and chemical factors). We begin with species because here the language is most developed (Table 1).

1. Surrogate species terminology is quite easy to distill into indicator surrogates and management surrogates because we have a well-established term, “indicator species”, clearly linked to measuring one component of an ecosystem to represent another component, as well as two common terms, umbrella species and flagship species, which are primarily linked to management (Caro 2010). The indicator species concept has many different refinements (e.g., sentinel species, biomonitoring species, ecological-disturbance indicator species; Caro 2010) and has been extended to include indicator taxa (e.g., lichens; Brunialti et al. 2009) and using species traits (Moretti & Legg 2009). Simply counting species to estimate species richness is a commonly used indicator surrogate, sometimes employed to estimate the species richness of a different taxon, sometimes used to assess the status of an ecosystem (Fleishman et al. 2006). The management surrogate concept can also be extended from individual species to umbrella taxa (see the Important Bird Areas program; BirdLife International 2004) and umbrella guilds (Drever et al 2010), and it is related to other approaches for identifying species that might be particularly important for management, such as keystone species or landscape species (Caro 2010).

2. Ecosystems, like species, have well established roles as both indicator surrogates and management surrogates, but the terminology is not as explicit. One rarely hears of indicator ecosystems, umbrella ecosystems, or flagship ecosystems, even though it could be argued that coral reefs and rainforests are flagships due to their public prominence. The areal extent of an ecosystem is the most commonly used index of its indicator surrogacy value, although spatial configuration or connectivity are sometimes evaluated too. It is also common to measure ecosystem components such as vegetation structure (Noss 1990) as indicators of overall

condition. Ecosystems also have a critical role as management surrogates in the context of maintaining biodiversity at the species and genetic levels, i.e., the so-called coarse-filter strategy (Hunter et al. 1988), and thus conservation planning to maintain a representative array of ecosystems is well-established (Groves 2003).

3. Ecological processes are commonly used for indicator surrogacy; in particular measurements of such key features as ecosystem productivity and biogeochemical cycling are used as indicator surrogates for ecosystem condition (Noss 1990). Additionally, in recent decades, some processes that can be manipulated or even emulated have become management surrogates. For example, fire can be a management surrogate because ecosystem managers in fire-prone ecosystems often seek to maintain fire regimes that meet ecological and societal goals, including the provision of habitat for fire-dependent species (Bradstock et al. 2012). In forestry, the idea of emulating natural disturbance and succession regimes through specific timber management practices has meant that these processes are used as management surrogates tied to larger goals such as biodiversity and ecological integrity (Hunter & Schmiegelow 2011).

4. Abiotic factors are widely used as indicator surrogates; e.g., monitoring dissolved oxygen or pH to understand lake condition. It is also common for abiotic factors to be used as management surrogates. For example, when climate mitigation strategies are organized around reducing atmospheric CO_2, then CO_2 is a management surrogate for the much larger, more complex climate system. Management surrogacy centered on abiotic factors is the foundation of proposals to adapt to climate change by designing reserve systems around enduring abiotic factors such as topography, geology, and hydrology (Beier & Brost 2010, Beier et al. 2015).

5. Genetic metrics have a steadily growing role as indicator surrogates through genetic monitoring (Schwartz et al. 2007), especially in relation to genetic erosion (Hoban et al. 2014),

effective population size (Tallmon et al. 2012), and landscape connectivity (Baguette et al. 2013). Genetics also has a role as a management surrogate, particularly because maintaining genetic diversity is a means to achieve the larger goal of safeguarding evolutionary potential (Harrisson et al. 2014) and resilience (Schindler et al. 2010).

In summary, we recognize that both indicator surrogates and management surrogates are widely used across diverse components of ecological systems (Table 1). The use of indicator surrogates is more established, but the use of management surrogates is increasing in response to broad goals like maintaining ecosystem integrity and biodiversity.

Table 1. Examples of indicator surrogates and management surrogates for five types of ecological components. The example goals highlight distinctions between monitoring and managing. We chose these five classes to show the wide applicability of our concept, not to suggest that they constitute a definitive classification (e.g., one could readily combine ecosystems and ecosystem processes or separate abiotic factors into chemical and physical factors).

Class	**Indicator surrogates**		**Management surrogates**	
	Example	**Example Goal**	**Example**	**Example Goal**
Species	Indicator species	Detect change in target species abundance (E. coli, Ashbolt et al. 2001)	Umbrella species	Conserve a large suite of species (Leadbeater’s possum, Lindenmayer 1996)
	Indicator guilds	Detect change in function provided by a guild (pollinators, Kehinde and Samways 2012)	Flagship species	Foster support for conservation (giant panda, Bowen-Jones & Entwistle 2002)

Ecosystems	Ecosystem extent	Use species-area relationships to predict species richness (Triantis et al. 2015)	Ecosystems as coarse filters	Maintain biodiversity at species and genetic level by conserving a representative array of ecosystems (Hunter et al. 1988)
	Ecosystem structure	Measure structural diversity to quantify habitat for target species (Baril et al. 2011)		
Ecological processes	Ecosystem productivity	Detect changes in biomass accumulation (Culman et al. 2010)	Disturbance regimes	Manage fire regimes to create desired vegetation (Bradstock et al. 2012)
	Biogeochemical cycling	Detect carbon fluxes (Fan et al. 2015)	River flows	Manage flow regimes to restore riverine ecosystem integrity (Beechie et al. 2010)
Abiotic factors	Nutrient concentration	Monitor nitrogen and phosphorous water pollution (Rocha et al. 2015)	Geological and climatic diversity	Conserve diverse environments for biodiversity (Beier et al. 2015)
Genetics	Population structure	Detect functional connectivity (Braunisch et al 2010)	Genetic diversity	Maintain evolutionary potential (tuatara, Miller et al. 2012)

Benefits of setting clearer goals

The main advantage of our proposed construct is that it gives explicit recognition of two overarching goals for ecological surrogacy that are linked but conceptually separate: to provide information about ecological systems and to facilitate their management. By seeing how this concept and related terms fit together (Table 1), it should be clearer how different disciplines might better learn from each other, and open up new opportunities for synthetic thinking and analysis. People as diverse as those who monitor lichen uptake of air pollutants (Brunialti et al. 2009) and those who try to assess the ecosystem services of oceans (Halpern et al. 2012) need to speak a common language, or at least agree on some fundamental ideas to foster cross-disciplinary learning. It is particularly important to recognize that an imperfect indicator surrogate might still serve as a useful management surrogate, and vice versa. Furthermore, the science underpinning each kind of surrogate may not be transferable, and research on each should be framed and assessed in relation to specific explicit goals.

We have argued that disagreements over the utility of ecological surrogates may reflect a misalignment of the goals of people who use indicator surrogates versus management surrogates (see Westgate et al. 2013). Such differences might also reveal a schism in opinions about the value of quantitative information for improving conservation outcomes. As scientists, we have an implicit bias toward evidence-based approaches (e.g. Sutherland et al 2004) and this may blind us to policy and public communication benefits of management surrogates that can be difficult to quantify. For example, promoting flagship or umbrella species can lead to large conservation gains, particularly if stakeholders are more likely to embrace a single charismatic species than a set of ecological metrics serving as indicator surrogates (Schultz 2011). In short, disagreements over the utility of surrogates may reflect deeper arguments about the role of scientific information in conservation practice (Mace 2014).

In conclusion, ecological surrogacy is widely used by natural resource management organizations around the world, and that usage will probably increase because of its potential expediency and efficiency. To avoid unproductive and circular debates, we have sought clarity by explicitly recognizing two different (but equally legitimate) core uses for ecological surrogacy. We argue that evidence of surrogate efficacy may be based on the success of a management program (e.g., increased public support following a flagship species campaign), or documentation of a tight ecological relationship between a surrogate and its target (e.g., linking population viability of a species to ecosystem integrity), or both. Recognizing that different stakeholders have different goals when using surrogates should foster communication and collaboration across a wide range of disciplines, and thus build a multi-disciplinary foundation for effective ecological management.

Acknowledgments

The work in this paper was funded by the Australian Research Council though a Laureate Fellowship to DBL. Tabitha Boyer and Claire Shepherd assisted with many aspects of workshop organization that brought together the co-authors of this article and subsequent manuscript preparation. Paul Beier, Bonnie Lamb, Lee O'Brien, and Greg Shriver reviewed earlier drafts of this manuscript.

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