REVIEW

Identifying, preventing and mitigating ecological traps to improve the management of urban aquatic ecosystems

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Summary

1. Urbanization alters the environmental characteristics of aquatic ecosystems, often reducing the availability and quality of habitats for animals. Improving the condition of urban water-bodies is increasingly important, but management activities could have unintended outcomes that increase the extinction risk for animals.

2. A mismatch can exist between human perceptions of habitat quality, and what represents functional habitats for animals. This can lead to animals not responding to management activities, if presumed high-quality habitats are unsuitable. More seriously, the fitness of animals could be compromised by management activities, especially if animals prefer threatening habitats resulting in an ecological trap.

3. Ecological traps can drive populations to extinction and may arise directly from management activities. However, there has been limited work on how to best manage traps despite their important implications for the conservation and management of animal populations.

4. We illustrate how urban management activities could cause ecological traps, and potential ways that traps could be managed. We outline a decision framework to identify, prevent and mitigate ecological traps, and illustrate this framework using stormwater wetlands as a case study. Stormwater wetlands have many features of natural wetlands but accumulate pollutants as part of the stormwater treatment process and there is a high likelihood some are traps. If so, this will be an important environmental issue, given the rate at which these wetlands are being created around many cities.

5. Synthesis and application. Ecological traps that arise as unintended outcomes of management activities could represent a serious but currently underappreciated environmental problem. Our study will help minimize the risk that management activities inadvertently decouple habitat selection cues from habitat quality, and mitigate the potential consequences for animals when this does occur. This is an important step to ensure that management activities achieve desired ecological outcomes and do not result in unintentional environmental degradation.

Key-words: anthropogenic change, maladaptive habitat selection, rehabilitation, restoration, stormwater wetlands, urbanization

Introduction

While humans have changed much of the earth’s surface (Vitousek et al. 1997), some of the most dramatic alterations are due to urbanization (Grimm et al. 2008). Currently, >50% of the world’s population lives in cities, with further increases expected over the next 50 years (Grimm et al. 2008). Most major cities are established around rivers, which provide a myriad of important ecosystem services (Grimm et al. 2008). Ensuring that water resources are used sustainably so that these services continue in the face of urbanization is a global challenge.
Urbanization alters the biological, chemical and physical characteristics of aquatic ecosystems. The ‘urban stream syndrome’ (Walsh et al. 2005) encapsulates a raft of changes (e.g. hydrological, geomorphic, chemical) that often reduce the availability and quality of habitats for animals. Although urban development commonly leads to a net loss and fragmentation of habitats, it may also result in the creation of new ones (e.g. wetlands constructed as part of housing developments).

Improving the condition of streams has been a recent global focus (Bernhardt & Palmer 2007), including in urban areas (Violin et al. 2011). These efforts are often undertaken to provide habitats for aquatic organisms, or to improve water quality that will indirectly affect habitat conditions. However, few studies assess whether management activities actually enhance habitats or whether biota respond (Violin et al. 2011). When they do, animals can often exhibit weak or variable responses (e.g. Lepori et al. 2005).

Inconsistent responses may be due to management activities being undertaken at insufficient scales, or to the influence of other limiting factors (e.g. hydrology; Bond & Lake 2003). Alternatively, animals may fail to respond because of mismatches between human perceptions of habitat quality, and what are functional habitats (Van Dyck 2012). For example, conservation planning frequently relies on mapping structural habitats (e.g. vegetation, land cover) and then correlating biotic changes with these environmental variables to identify likely factors. However, these measures can be poor surrogates for the environmental conditions that impact organisms (Mitchell & Powell 2003). Sometimes these mismatches will have a neutral environmental consequence, that is animals not responding to the creation of habitats incorrectly presumed to be suitable. These incorrect assumptions, however, can have more serious consequences if they compromise individual fitness because animals cannot discern between beneficial and threatening habitats.

Habitat selection should maximize the fitness of animals, even in the face of landscape alteration. To adaptively select habitats, animals often use indirect cues to assess current or future conditions (Schlaepfer, Runge & Sherman 2002). However, humans are altering habitats at rates faster than natural forms of environmental change [i.e. human-induced rapid environmental change (HIREC); Sih 2013]. If HIREC results in different conditions to those under which behaviour has been shaped, then an animal’s ability to make adaptive decisions can be compromised. If so, high-quality habitats may be avoided (a ‘perceptual trap’; Patten & Kelly 2010) or low-quality habitats where fitness is reduced may be preferred (an ‘ecological trap’; Schlaepfer, Runge & Sherman 2002; Robertson & Hutto 2006; Robertson, Rehage & Sih 2013). Perceptual traps arise when animals avoid habitats where their fitness would be higher than the ones they prefer (Patten & Kelly 2010). Few studies have demonstrated perceptual traps. The most convincing evidence comes from Lesser Prairie chickens in New Mexico, where herbicide application in grasslands decreased shrub cover, and females avoided nesting in low cover areas, despite comparable reproductive fitness in treated and untreated areas (Patten & Kelly 2010). Perceptual traps may result in failed management objectives and poor investment outcomes if high-quality managed habitats are avoided. Mitigating perceptual traps will require determining the specific cues animals use to select habitats, and manipulating these to attract animals to high-quality habitats (Patten & Kelly 2010).

Ecological traps will likely cause extinctions (Battin 2004) and can result from a wide range of anthropogenic activities. Unfortunately, habitat restoration is a major cause of traps (Robertson, Rehage & Sih 2013). For example, butterflies in Oregon USA prefer to oviposit on host plants in restored wetlands where seasonal flooding reduces survival (Severns 2011). The presence of an ecological trap could mean that three of the five criteria for ecologically successful stream restoration (following Palmer et al. 2005) are not met, with (i) ecological condition not being measurably improved; (ii) ecosystems failing to be self-sustaining and resilient and (iii) lasting harm being inflicted. Any management activity that alters habitat quality could cause traps, even if this occurs indirectly. For example, water withdrawals for agriculture could trap salmon in areas with poor water quality (Jeffres & Moyle 2012). Despite increased recent focus on understanding ecological traps (e.g. Schlaepfer, Runge & Sherman 2002; Robertson & Hutto 2006; Fletcher, Orrock & Robertson 2012; Robertson, Rehage & Sih 2013; Hale, Treml & Swearer 2015), there has been limited exploration of their applied implications (but see Battin 2004; Robertson 2012).

Here we present improved methods to help urban waterway managers prevent, identify and mitigate ecological traps. Although perceptual traps may have important applied implications too (Patten & Kelly 2010), we focus on ecological traps because they are likely to arise directly from management activities. We concentrate on urban aquatic ecosystems for four reasons: (i) the high rates of habitat transformation (i.e. likelihood of traps) around cities; (ii) the extensive efforts on improving habitat for animals in many urban areas; (iii) the range of important ecosystem services they provide and (iv) the lack of knowledge about ecological traps in aquatic ecosystems.

We first review how ecological traps may form and how they may be mitigated. We then highlight how common urban waterway management activities may cause traps, and how these could be managed. We conclude with a decision framework to better prevent and manage ecological traps, and illustrate some of its elements using the example of stormwater treatment wetlands.

How do traps form, and how could they be mitigated?

Managing ecological traps depends on understanding how they form. Robertson & Hutto (2006) proposed three
causes: (i) settlement cues are altered so that habitats appear more attractive but their suitability remains unchanged; (ii) habitat quality decreases but settlement cues remain unchanged so that habitats still appear suitable or (iii) both habitat quality and settlement cues change simultaneously. However, traps may form in three other ways. First, HIREC may result in novel or increased sources of irrelevant stimuli (i.e. ‘background noise’) that prevent animals from accurately assessing habitats, resulting in equal preferences for poor- and high-quality habitats (i.e. an ‘equal preference’ trap; Robertson & Hutto 2006). Changes to animals themselves could also cause traps, such as pollutant exposure affecting sensory biology that either prevents animals from assessing habitat quality and causes an equal preference trap, or results in them preferring poor-quality habitats (i.e. a severe trap). Thirdly, while preferences for natal-like habitats could help animals overcome traps (Kokko & Sutherland 2001), recent evidence suggests this could exacerbate the effects of traps (Hale, Treml & Swearer 2015). Natal habitat preference induction (i.e. NHPI; Davis & Stamps 2004) could lead to a reinforcement of preferences for poor-quality habitat and cause the initial development and persistence of traps, if negative feedback loops develop (i.e. individuals raised in polluted environments select these later in life).

Ecological traps caused by changes to habitat quality or cues can be mitigated by increasing the quality of traps, or reducing their attractiveness (Robertson & Hutto 2006). Option one requires identifying and subsequently improving the aspects of habitats that are the most important determinants of fitness. The second option requires identifying the cues used by trapped animals and manipulating these to reduce habitat attractiveness (Robertson 2012). Animals may also be excluded from poor-quality sites (e.g. via fencing). Managing traps caused by the three other mechanisms will be more difficult. Some animals can behaviourally adapt to changes in the background environment (e.g. birds adjusting their singing pitch in traffic noise; Slabekoorn & Peet 2003). For species that cannot (e.g. frogs and traffic noise; Lengagne 2008), actions must be taken to ensure the successful transmission of cues (e.g. by limiting traffic noise at crucial times). Preventative actions such as reducing pollutant exposure will be most effective for traps caused by changes to animals or NHPI. Examples of trap formation and mitigation related to urban waterway management are outlined in Supporting Information (Tables S1 and S2, Supporting Information).

Identifying the likely risks of ecological traps

Risk is often defined as the product of the likelihood of a hazard, and the consequences of that hazard if it occurs (i.e. Risk = Likelihood × Consequences: Hart et al. 2003). Modelling studies (e.g. Delibes, Gaona & Ferreras 2001; Donovan & Thompson 2001; Kokko & Sutherland 2001; Kristan 2003; Fletcher, Orrock & Robertson 2012) have highlighted several risks associated with traps, including: (i) traps usually lead to population extinctions; (ii) thresholds exist in terms of the proportion of trap habitat in the landscape above which deterministic extinctions occur; (iii) traps can be caused by decreased reproduction or survival; (iv) extinction occurs fastest when initial population sizes are small and (v) traps arising from degrading existing habitats are more likely to cause extinctions than new trap habitats. However, most studies have examined the effects of traps at local scales, rather than considering how these effects may scale up within the mosaics of habitat quality that are likely present across the landscape. Hale, Treml & Swearer (2015) recently showed that the risks of traps at these larger scales depend on: (i) the probability of encountering a trap; (ii) the likelihood of selection; (iii) the fitness costs of traps and (iv) species-specific vulnerability to these costs.

How could ecological traps in urban waterbodies be better managed?

Ecological traps could be caused by any activity that alters habitats, but there is limited information about how to best manage traps. We present a framework to identify and manage ecological traps that arise as unintended consequences of management activities (Fig. 1), which adapts and applies current knowledge about the principles of ecological stream restoration (e.g. Palmer et al. 2005; Lake, Bond & Reich 2007), and effective monitoring programme design (e.g. Lindenmayer & Likens 2009) to the management of ecological traps.

A framework for better managing ecological traps

DOCUMENT PROPOSED MANAGEMENT ACTIVITIES

Mapping the distribution of proposed activities is often used to prioritize sites for works (e.g. Llewellyn et al. 1996). This would help assess the scale of the problem if traps arise, by indicating the extent of overlap in the distribution and density of potential habitats and management activities. Management activities can be prioritized where the effects of potential traps can be minimized (e.g. away from critical habitats). However, it is important to note that broad categorizations of habitats (e.g. size, distribution) can be misleading if they poorly reflect the environmental variables organisms are responding to Miller & Hobbs (2007).

IDENTIFY HOW MANAGEMENT ACTIVITIES WILL AFFECT ANIMALS

To predict how animals will respond to management activities, information is needed about: (i) which species
inhabit the area; (ii) their habitat and life-history requirements; (iii) how these requirements may be affected by environmental changes caused by the activity and (iv) the consequences of these effects. Many agencies will have pre-existing information (e.g. surveys) that can be supplemented where necessary to address the first point. Although information about all life-history characteristics that may increase the risk of traps (Battin 2004; Hale, Treml & Swearer 2015) is unlikely to be available, an understanding of their basic traits (e.g. generation time, number of offspring, likely dispersal distances and frequency, likely population sizes, habitat selection behaviour) will help identify those likely to be at highest risk (i.e. species with traits from the ‘slow’ end of the ‘slow–fast’ life continuum, Reynolds 2003). Key knowledge gaps could be addressed with targeted research programmes.

Addressing the third and fourth points requires setting clear goals, crucial to any monitoring programme (Palmer et al. 2005; Lindenmayer & Likens 2009), and thinking carefully about the intended and potentially unintended responses to management activities. Ecological traps could represent a form of intervention-based ecological surprise (i.e. substantial and unanticipated changes in abundance from previously unsuspecting processes; Doak et al. 2008). Conceptual models can help define goals, and identify potential outcomes of management activities. To

Fig. 1. A decision framework for identifying and managing the effects of ecological traps arising from management activities.

understand ecological traps, goals must be included that test the null hypothesis that works do not decrease fitness, which extends the more common goals of monitoring programmes (e.g. to increase species richness or abundance).

ASSESS RISKS THAT MANAGEMENT ACTIVITIES POSE TO ANIMALS

A risk assessment based on the above information will help identify the likelihood that management activities could cause traps, and their likely consequences. Assessment frameworks exist for some activities (e.g. dam removal: Hart et al. 2002; stormwater wetlands: Tixier et al. 2011), which can be adapted to answer the following:

1. What is the activity?
2. What is the distribution of the activity?
3. What will the activity change in terms of habitats for animals?
4. What is the likelihood of these changes?
5. What are the likely consequences of these changes?

Risk will be highest when activities that have more deleterious effects on fitness (i.e. mortality) occur commonly in rapidly changing landscapes, and in conjunction with life-history traits that increase susceptibility. There is thus likely to be considerable interspecific variability in risks based on the distribution and life-history traits of animals, and the underlying characteristics of landscapes. Low-risk activities can proceed coupled with baseline monitoring to assess progress (e.g. changes in abundance) and to update hypothesized responses and assumptions in conceptual models, using principles of effective monitoring (e.g. Lindenmayer & Likens 2009).

INCORPORATE PREVENTION MEASURES INTO MANAGEMENT ACTIVITIES

Prevention measures could be incorporated into the design of management activities for high-risk species. A cost–benefit analysis should assess options based on cost, logistics and their likely effectiveness. Some options may be relatively inexpensive, while others will involve considerable time and resources (see Tables S1 and S2). A range of pre-existing approaches could be used to assess and prioritize different options (see Beechie et al. 2008). As demonstrated by Fuentes et al. (2014), it may be possible to maximize conservation outcomes within budget constraints using an integrative approach incorporating local knowledge, expert opinion and optimization software.

MONITORING TO ASSESS WHETHER MANAGEMENT ACTIVITIES REDUCE FITNESS

Three lines of evidence are required to demonstrate an ecological trap (Robertson & Hutto 2006): (i) animals must prefer (a ‘severe’ trap) or equally prefer (an ‘equal preference’ trap) one habitat over another; (ii) fitness must differ between habitats and (iii) animals prefer or equally prefer habitats where their fitness is lower than in other available habitats. Routinely assessing habitat selection behaviour is likely to be prohibitively expensive so a sensible approach would be to first test whether management activities decrease fitness, and if so, to consider habitat selection studies for high-risk species.

Structural indicators (e.g. biological diversity) are commonly monitored (Palmer & Febria 2012), but a wider variety will be required to assess changes in fitness. Inexpensive proxies may be suitable, for example measures of condition (e.g. length/weight relationships, swimming/flying performance, oxygen consumption for air- and water-breathing animals) and/or reproductive traits (e.g. gonadosomatic index, size/fecundity relationships). As traps could arise for non-target taxa (e.g. Jeffres & Moyle 2012), several taxa may need to be assessed.

ASSESS WHETHER HABITAT SELECTION STUDIES ARE WARRANTED

An ecological trap has not been created if fitness has not decreased but reduced fitness does not necessarily equate to ecological traps. Urban landscapes likely function as metapopulations i.e. spatially segregated populations connected by dispersal (Levins 1970). Variability in habitat quality across urban landscapes is likely, and this often influences vital demographic rates such as reproduction, dispersal and survival and thus the persistence of local populations (Kindvall 1996; Franken & Hik 2004). This can lead to source-sink dynamics, where poor-quality habitats cannot support local populations without replenishment from other patches (Pulliam 1988; Dias 1996). Ecological traps and source-sink dynamics are related, but differ in that the latter can occur in the absence of impacts on habitat selection (Battin 2004). Distinguishing whether poor-quality habitats are sinks or ecological traps is likely to be important for managers. Source-sink dynamics as defined originally (Pulliam 1988; Pulliam & Danielson 1991) assume an ideal free or ideal despotic distribution, with sinks only used when density becomes high in source habitats and the two thus having similar fitness benefits. In comparison, ecological traps will have considerably more severe effects on population persistence as animals are attracted from higher to lower quality habitats, increasing the risk of local extinctions in both trap and non-trap habitats. The potential risks that undiagnosed ecological traps pose should be considered before conducting habitat selection studies. Sometimes, it may be acceptable for management activities to proceed even with the potential that traps will arise. For example, an undiagnosed trap that leads to slightly reduced breeding for an abundant, widely distributed species will likely be of less concern than those that cause mortality, or affect rare or endangered species. It is possible that some traps could also have desired outcomes, for
example by reducing the abundance of noxious animals (Letnic et al. 2015).

**TEST WHETHER POOR-QUALITY HABITATS ARE PREFERRED**

Five methods can be used to test whether animals show habitat preferences (Robertson & Hutto 2006): surveys to document patterns of settlement, the distribution of dominant individuals, site fidelity or temporal variances in population size, or alternatively manipulative choice experiments. These differ in terms of their degree of sensitivity, associated logistics, and the animals they are most suitable for (Table 1). The first four are correlative and thus do not provide definitive evidence of habitat preferences (Crowe & Underwood 1998). The strongest evidence comes from experiments, but their design must ensure they can demonstrate a preference (Olabarria, Underwood & Chapman 2002), are not affected by experimental artefacts (Skelly 2002) and replicate natural conditions. Multiple lines of evidence will provide the strongest case (Robertson & Hutto 2006), especially incorporating both experiments and observational studies.

**ASSESS AND IMPLEMENT MITIGATION MEASURES**

If an ecological trap has formed, then its effects will need to be mitigated, but determining how to do so depends on understanding what is causing the trap. For example, a trap for frogs in wetlands due to heavy metal pollution could be mitigated by reducing heavy metals, or by fencing wetlands to prevent colonization. In comparison, mitigating a trap for native fish caused by barrier removal facilitating movement to upstream areas with competitively superior invasive fish may require widespread management of the introduced species. Different options should be assessed using a similar cost–benefit to the evaluation of preventative measures.

If undertaking post hoc actions to effectively mitigate traps is impossible, management strategies could be revised to control where future traps are likely to arise. For example, traps caused by barrier removal as discussed above could be mitigated by avoiding catchments where introduced species are known to be present.

**Stormwater wetlands as a case study to demonstrate the ecological traps decision framework**

Stormwater is a major threat to waterway health (Walsh et al. 2005), and wetlands are often constructed to capture and treat runoff prior to discharge into urban waterbodies. However, these wetlands attract wildlife (Tixier et al. 2011), exposing them to pollutants and potentially causing a range of lethal and sublethal effects (e.g. Snodgrass et al. 2008). Stormwater wetlands are potentially ecological traps, given they: (i) are used as habitat by aquatic organisms; (ii) likely possess many characteristics of natural wetlands (e.g. native vegetation); (iii) are designed to treat a range of pollutants (e.g. sediment, nutrients, heavy metals, biocides) that could compromise the fitness of animals and (iv) provide habitat options in urban landscapes where much habitat has been lost (Brand & Snodgrass 2010). There is thus a potential conflict between the primary functions of stormwater wetlands and their value as habitats for animals (Hamer, Smith & McDonnell 2012).

We focus on the region around Melbourne in southern Australia. As with many other cities worldwide (e.g. Kentula, Gwin & Person 2004), wetlands are being constructed at a rapid rate (Fig. 2, Fig. S1). Serious and widespread environmental problems may therefore arise if stormwater wetlands are ecological traps. We illustrate below how our framework could be used to explicitly test whether this is the case.

**DOCUMENT PROPOSED STORMWATER WETLANDS**

Wetland construction has increased rapidly around Melbourne in the past several decades (Fig. 2). However, there are areas where wetlands are more heavily concentrated (Fig. S1), and thus where more serious environmental problems may arise if some are traps. Environmental conditions are likely to vary considerably between wetlands (Fig. S2), with some containing heavy metal concentrations well above the Interim Sediment Quality Guidelines (ISQG) high trigger values (ANZECC & ARMCANZ 2000).

**IDENTIFY HOW STORMWATER WETLANDS WILL AFFECT ANIMALS**

Melbourne Water, the agency responsible for constructing the vast majority of artificial wetlands, has strict guidelines to improve the effectiveness of wetlands in treating stormwater, and maximize their environmental and social benefits (MW 2010). However, animals may still be negatively affected by changes to habitat conditions that occur during wetland construction, operation and maintenance (Fig. 3, Table 2). There are several potential causes including: changes to wetland form (e.g. earthworks) and vegetation (e.g. removal, herbicides), negative interactions with invasive species, exposure to polluted water and sediment (from the stormwater treatment process and accidental spills) and altered hydrology. Animals may be exposed to these poor-quality wetlands increasingly during drought, as less permanent habitats dry.

**ASSESS RISK THAT STORMWATER WETLANDS POSE TO FROGS**

A range of taxa have been used as indicators to assess the ecological condition of wetlands (Tixier et al. 2011) and...
may be responsive to the environmental changes outlined above. We use frogs and changes in water and sediment quality to demonstrate our framework. These changes have a high likelihood of occurrence and frogs are likely to be highly susceptible based on previous studies demonstrating that stormwater exposure can cause a range of lethal and sublethal effects (e.g. Snodgrass et al. 2008; Ruiz et al. 2010). Heavy metal pollution may be contributing to global declines of amphibians (Hopkins & Rowe 2010). Both their highly permeable skin and larval feedings habitats (e.g. ingesting sediment) (Hopkins & Rowe 2010; Ficken & Byrne 2013) may increase their susceptibility. Around Melbourne, Banjo frogs *Limnodynastes dumerilii* may be particularly susceptible given they burrow in wetland sediments and spawn in rafts that are attached to riparian vegetation and exposed to potential waterborne pollutants during development. Other contaminants (e.g. triazine herbicides) could also have negative effects on frogs (Hayes et al. 2002). In contrast, invasive mosquitofish *Gambusia holbrooki* have life-history traits (e.g. widespread distribution, tolerance of wide range of environmental conditions, high fecundity, responsiveness to multiple cues using different sensory modalities; Pyke 2008; Ward & Mehner 2010) likely to reduce their sensitivity to ecological traps. The construction of artificial wetlands may facilitate the spread of mosquitofish and sympatry with native frog species. Given their negative impacts (e.g. via egg or tadpole predation; Pyke 2008), mosquitofish could cause wetlands to become ecological traps for frogs.

### Table 1. Evaluating methods to test for habitat preferences

<table>
<thead>
<tr>
<th>Method</th>
<th>Indicator of preference</th>
<th>Method considerations</th>
<th>Logistical requirements</th>
</tr>
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<tbody>
<tr>
<td>1. Settlement patterns</td>
<td>First selected habitat should represent preference relative to other habitats for migratory species (e.g. birds, insects) that select new breeding habitats annually</td>
<td>May not correlate with habitat preference if there are alternative habitat selection strategies within a population (e.g. between age classes/morphs). Other factors could influence habitat selection between years (e.g. changing physiological needs). Settlement patterns can be confounded by differential post-settlement mortality</td>
<td>Monitoring a range of habitats throughout the breeding season</td>
</tr>
<tr>
<td>2. Distribution of dominant individuals</td>
<td>Dominant individuals are likely to be found disproportionately in preferred habitats</td>
<td>Suitable for social species with a clear dominance hierarchy. Requires understanding of dominance hierarchy (see Neumann et al. 2011)</td>
<td>Detailed information may be required to assess the dominance hierarchy, although proxies (e.g. size) may be suitable</td>
</tr>
<tr>
<td>3. Site fidelity</td>
<td>Higher site fidelity and lower emigration rates should occur in preferred habitats</td>
<td>Suitable when rates of site fidelity and emigration can be tracked via direct observations or tagging</td>
<td>Sample sizes likely to be limited by logistical constraints, for example cost of GPS collars</td>
</tr>
<tr>
<td>4. Temporal variance in population size</td>
<td>Variance should be lower in preferred habitats</td>
<td>Other factors could influence variance in population size, for example degree of connectivity with other habitats</td>
<td>Multiple years of monitoring needed</td>
</tr>
<tr>
<td>5. Choice experiments</td>
<td>Preferences inferred from responses to different habitats, or cues representing different habitats</td>
<td>Unlikely to be suitable for some species, for example large animals, those difficult to catch in sufficient numbers. Microcosm experiments may not reflect complexity of habitat selection in natural settings</td>
<td>Cost likely to be low</td>
</tr>
</tbody>
</table>

Adapted and expanded from Robertson & Hutto (2006).

![Figure 2](image_url) Fig. 2. Wetland construction in the greater Melbourne metropolitan region 1985–2014. Data from Melbourne Water Corporation. Construction date was unknown for 14 wetlands.
INCORPORATE PREVENTION MEASURES INTO STORMWATER WETLAND DESIGN

A variety of methods could be used to prevent traps for frogs caused by altered water and sediment quality, and these are likely to vary in terms of both associated costs and likely effectiveness (Table S3). For example, alternative stormwater treatment measures may be effective at reducing runoff, but need to be implemented at large scales, and thus have high associated costs. In contrast, it will be less expensive to replant or remove vegetation around wetlands to reduce their attractiveness to animals, but the effectiveness of this method depends on knowing the specific cues that animals are using to select wetlands. Similar to Fuentes et al. (2014), potential options could be evaluated by ranking their likely effectiveness, feasibility, cost and opportunity, and decision support software used to model the performance and cost-effectiveness of a range of different management scenarios.

MONITORING TO ASSESS WHETHER STORMWATER WETLANDS REDUCE FROG FITNESS

Frogs use wetlands around Melbourne as habitat, and correlative links have been demonstrated between abundance and/or occurrence and a range of local and landscape environmental variables for a variety of species (e.g. Hamer & Parris 2011; Hamer, Smith & McDonnell 2012; Ficken & Byrne 2013). Stormwater exposure can reduce fitness in microcosm studies (e.g. Snodgrass et al. 2008), and the specific heavy metals observed in high concentrations around Melbourne have deleterious effects on frogs in other areas (e.g. copper: Lance et al. 2012). Biological impairment of aquatic organisms at the community, population and individual levels is also likely to have occurred in response to heavy metals and pesticides within the region (Kellar et al. 2014).

Few published studies, and none in our study region, have tested how fitness varies among stormwater wetlands. Reciprocal transplant experiments are a useful tool to examine differences in fitness between habitats, but moving frogs between wetlands is not feasible due to the risk of spreading the fungal disease Batrachochytrium dendrobatidis. Gallagher et al. (2014) illustrate how a combination of field and laboratory methods could be a useful approach in future studies, by using surveys to relate frog occurrences to pollutant conditions, and microcosm experiments to examine the effects of these pollutants on a range of potential indicators such as size at metamorphosis, survival and development rate, abnormalities and biomarkers such as oxidative stress responses (e.g. Falfushinska et al. 2008; Snodgrass et al. 2008; Hamer, Smith & McDonnell 2012).

ASSESS WHETHER TARGETED HABITAT SELECTION STUDIES WITH FROGS ARE WARRANTED

There is a strong rationale for predicting that frogs around Melbourne might be existing as metapopulations. If fitness differs between wetlands, then assessing whether habitat selection is adaptive or not will be important. Frogs are often assumed to form metapopulations, based on their limited dispersal ability, strong site fidelity and spatially distinct breeding populations, although often these assumptions are not explicitly tested (Alford & Richards 1999; Smith & Green 2005). Classic metapopulation theory is likely to accurately describe the dynamics of the growing grass frog Litoria raniformis in peri-urban wetlands around Melbourne (Heard, Scroggie & Malone 2012). However, whether these or other species are adaptively selecting habitats remains unexplored. If some wetlands are ecological traps, they may be drawing frogs from higher quality into low-quality wetlands, increasing the risk of both local and regional extinctions.
Table 2. Assessing the risks that stormwater wetlands could result in ecological traps for frogs in the greater Melbourne metropolitan area

<table>
<thead>
<tr>
<th>Likely changes to habitats that could cause traps</th>
<th>What is the likelihood of these changes?</th>
<th>What are the consequences of these changes for the fitness of animals?</th>
<th>Overall risk (likelihood × consequence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Water and sediment quality</td>
<td>Certain Wetlands accumulate pollutants during the intended treatment process</td>
<td>Major Exposure to stormwater can cause mortality or sublethal effects (e.g. Snodgrass et al. 2008)</td>
<td>Very high</td>
</tr>
<tr>
<td>2. Altered hydrological regimes</td>
<td>Likely Most wetlands will be perennial but may have flashier hydrology</td>
<td>Moderate Fitness could be affected, for example by desiccation of eggs laid in temporarily higher water levels or larvae/tadpoles becoming trapped as water levels water</td>
<td>High</td>
</tr>
<tr>
<td>3. Altered wetland form/area</td>
<td>Unlikely, as most wetlands are constructed in cleared areas</td>
<td>Moderate Effects likely to be more severe if pre-existing wetlands are destroyed/modified</td>
<td>Medium</td>
</tr>
<tr>
<td>4. Changes in vegetation</td>
<td>Likely Existing vegetation is retained where possible, but removal is likely during construction/maintenance. Wetlands are planted with local indigenous tubestock</td>
<td>Major When vegetation removal occurs (e.g. during wetland resetting), it may be considerable. Aquatic vegetation may be a key habitat feature for some species (e.g. Hamer, Smith &amp; McDonnell 2012)</td>
<td>Very high</td>
</tr>
<tr>
<td>5. Invasive species (e.g. via competition, predation, antagonistic interactions)</td>
<td>Likely Invasive mosquitofish are commonly observed in wetlands (e.g. Hamer &amp; Parris 2013; R. Coleman unpublished data)</td>
<td>Major Mosquitofish can have serious deleterious impacts on frogs (Pyke 2008)</td>
<td>Very high</td>
</tr>
</tbody>
</table>


If fitness differs between wetlands, three factors need to be considered to test whether poor-quality ones are ecological traps. First, which species are affected, how is their fitness being reduced and by what magnitude? Concern will be greatest when species suffer large fitness costs, especially those that are conservation listed (e.g. the endangered growling grass frog around Melbourne: IUCN 2015). Secondly, is fitness correlated with environmental quality (e.g. water and sediment quality)? Thirdly, how widespread are wetlands with these characteristics? Risk will be highest if fitness is lower in polluted wetlands, and these represent a large proportion of available habitats.

TEST WHETHER POOR-QUALITY HABITATS ARE PREFERRED BY FROGS

No studies have been undertaken to test whether frogs exhibit preferences for particular wetlands within the region. However, surveys have demonstrated that the composition of frog communities is likely related to environmental factors (e.g. shading, predatory fish, aquatic vegetation) and
that there is interspecific variability in responses to these factors (Hamer & Parris 2011).

In the future, multiple approaches will provide the strongest basis to assess whether frogs prefer wetlands with particular habitat characteristics and thus whether those where fitness is reduced are ecological traps. Combining field surveys to examine temporal variances in population sizes with experiments to examine habitat preferences is likely to be most effective. Field surveys will require repeated visits to sites (Heard, Robertson & Scroggie 2006), and potentially multiple methods to sample adult (e.g. surveys, listening to calls; Heard, Robertson & Scroggie 2006) and larval (e.g. bottle traps, fish traps, dip netting, direct observations – Hamer & Parris 2011) frogs. Microcosm-based choice experiments are an effective method to examine habitat preferences for frogs (e.g. Kraus & Vonesh 2010). This would involve assessing colonization of microcosms established to simulate different environmental wetland conditions (e.g. sediment and water quality, presence/absence of aquatic vegetation and predatory fish).

**MITIGATION MEASURES**

Mitigating traps by reducing the attractiveness of wetlands or preventing colonization could use the same methods to prevent traps (Table S3). However, mitigation methods would be implemented after traps have been detected, rather than as they are being constructed. Alternatively, efforts could be undertaken to improve the suitability of trap wetlands as habitat for frogs, for example by improving wetland/sediment quality through remediation of polluted sediments, or removing invasive fish (e.g. mosquitofish) by draining and refilling the wetland (Table S3).

**CONCLUSIONS**

Although there is great potential that management activities in urban ecosystems inadvertently create ecological traps, this possibility remains unexplored. Our flexible and adaptable decision framework will improve the likelihood that management activities achieve desired outcomes and are not undermined by unintended ecological degradation. There has been little progress in developing practicable guidelines to manage ecological traps in the decade since Battin (2004) stated that ‘we cannot afford to ignore the possibility of ecological traps, or fail to take them into account in the study, management and conservation of animal populations’. Our review represents an important step in this process, to help identify when management activities may have inadvertently decoupled habitat selection cues and habitat quality and how to minimize the potential consequences for animals.

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**Data accessibility**

Data have not been archived because this article does not contain data.

**References**


Supporting Information

Additional Supporting Information may be found in the online version of this article.