

FORUM

Engineering a future for amphibians under climate change

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Summary

1. Altered global climates in the 21st century pose serious threats for biological systems and practical actions are needed to mount a response for species at risk.
2. We identify management actions from across the world and from diverse disciplines that are applicable to minimizing loss of amphibian biodiversity under climate change. Actions were grouped under three thematic areas of intervention: (i) installation of microclimate and microhabitat refuges; (ii) enhancement and restoration of breeding sites; and (iii) manipulation of hydroperiod or water levels at breeding sites.
3. *Synthesis and applications.* There are currently few meaningful management actions that will tangibly impact the pervasive threat of climate change on amphibians. A host of potentially useful but poorly tested actions could be incorporated into local or regional management plans, programmes and activities for amphibians. Examples include: installation of irrigation sprayers to manipulate water potentials at breeding sites; retention or supplementation of natural and artificial shelters (e.g. logs, cover boards) to reduce desiccation and thermal stress; manipulation of canopy cover over ponds to reduce water temperature; and, creation of hydrologically diverse wetland habitats capable of supporting larval development under variable rainfall

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regimes. We encourage researchers and managers to design, test and scale up new initiatives to respond to this emerging crisis.

Key-words: adaptation management, desiccation, hydroperiod, microclimate, microhabitat, refuge, restoration, thermal stress

Introduction

Amphibians have already suffered massive losses as a consequence of ongoing stressors including disease, habitat loss, pollution and over-utilization (Stuart *et al.* 2004). Climate change will be likely to exacerbate most of these threats and will pose major new challenges for conservation practitioners in the coming century (Corn 2005; Blaustein *et al.* 2010). General guidelines exist for managing biodiversity under climate change (e.g. Hannah *et al.* 2002); however, relatively few empirical case studies examine the efficacy of practical 'adaptation management' (Heller & Zavaleta 2009) that might aid in amphibian conservation. Adaptation management is a term used by natural resource managers to describe actions to forestall threats to natural systems; it does not refer to adaptation in an evolutionary sense nor iterative and corrective decision making in the face of imperfect knowledge.

Our goal in this article is to identify specific management actions that could be tested to generate more effective management systems. We do not provide an exhaustive survey of adaptation management principles for amphibians under climate change. Rather, we focus on potentially valuable engineering solutions designed worldwide to ameliorate impacts and provide more effective recovery and maintenance of amphibian populations under uncertain climate. We comment on three thematic areas of intervention conceived to reduce exposure to heat and water stress in amphibians: (i) installation of microclimate and microhabitat refuges; (ii) enhancement and restoration of breeding sites; and, (iii) manipulation of water levels at breeding sites. Although some of these actions have been applied, many have not yet been tested in the context of climate-related amphibian conservation. Others are derived simply from ecological reasoning with few empirical case studies available to demonstrate feasibility and effectiveness.

Installation of microclimate and microhabitat refuges

Reducing exposure to stressful conditions is critical to minimize vulnerability and impacts of climate change (Williams *et al.* 2008). Intensive management to modify habitats may be needed to preserve some species (Peters & Darling 1985). The small spatial scale at which most amphibians operate provides some unique opportunities for management intervention in this regard. Mitchell (2001) used artificial wetting via portable irrigation sprayers to manipulate water potentials at breeding sites for the terrestrial toadlet *Pseudophryne bibronii* in South Australia. The manipulation resulted in increased calling activity, matings and oviposition in wet nests suitable for embryonic development. Broader implementation could improve hydra-

tion states and breeding success of terrestrial breeding frogs with restricted ranges. For example, intervention could target Papuan leaf-litter microhylid frogs suffering reproductive failure during El Niño Southern Oscillation droughts (Bickford 2005) or Central American terrestrial-breeding rain frogs (*Diasporus diastema*, formerly *Eleutherodactylus*) that undergo population crashes during extended periods of dry days (Pounds, Fogden & Campbell 1999). Trials are needed to determine whether artificial misting might reduce water stress on amphibian populations affected by a rise in height of orographic cloud base (Pounds, Fogden & Campbell 1999).

In many places, temporal redistribution of water resources will probably be needed. Irrigation systems coupled with storage devices in a range of situations may capture water during the wet season for release during the dry season. Sprinkler systems have already been used to compensate critical habitat lost as a consequence of water diversion for hydroelectricity in Tanzania (e.g. the Kihansi spray toad *Nectophrynoides asperginis*, Krajick 2006). Artificial misting of waterfalls have partially stabilized the decline of wetland plants (Quinn *et al.* 2005) but, the effectiveness of these types of systems for amphibians is unclear (Krajick 2006).

Shelter microhabitats are known to influence body temperatures and govern dehydration rates in amphibians (Seebacher & Alford 2002). Retention and supplementation of these microclimate refuges can aid species persistence, especially in locations with high water stress. Many amphibians seek refuge in logs or other wood refuges created by tree falls and other disturbances (Stewart 1995) and retention of down wood reduces desiccation and promotes amphibian survival in modified landscapes such as harvested forests (Rittenhouse *et al.* 2008). However, it is uncertain what constitutes a suitable natural shelter. In Washington, USA, logs used as nesting habitat by Van Dyke's salamander *Plethodon vandykei* supported stable microclimates throughout the hottest and driest time of the year (Blessing *et al.* 1999). Some woodland salamanders appear to be associated with larger logs (e.g. *Aneides ferreus*, *Batrachoseps wrighti*, Jones, Leonard & Olson 2005). Coarse woody debris may be supplemented or recruitment assisted in degraded or highly managed forests. Approaches to accelerate growth of large trees in managed forest landscapes are being tested to provide these types of habitats, in addition to late-successional forest conditions needed by a host of other taxa (Cissel *et al.* 2006).

Whitfield *et al.* (2007) documented systematic community-wide collapse of populations of terrestrial amphibians in Costa Rica, and postulated that declines were the result of climate-driven reductions in standing leaf litter. Litter supplementation may be beneficial in this regard, and litter supplementation has been shown to increase juvenile dendrobatid frogs (Donnelly 1989).

Artificial shelters or burrows are useful supplemental refuges for reptiles (Webb & Shine 2000; Souter, Bull & Hutchinson 2004), but have not been well tested for amphibians. One difficulty is that habitat requirements for most species are virtually unknown. Amphibians have been encountered under cover boards deployed for surveys (Latham & Knowles 2008) and, presumably, PVC pipes also constitute suitable shelters for some amphibians (Moulton, Fleming & Nerney 1996). Temperature regimes in such artificial shelters are typically more variable than under natural cover (Houze & Chandler 2002). Therefore, further studies are needed to both increase our understanding of microhabitat requirements of amphibians, and also to test alternative shelter designs (Lettink & Cree 2007; Arida & Bull 2008).

High temperatures can negatively impact egg and larval development. Canopy cover over ponds influences amphibian diversity in wetlands because species differ in their tolerance to shade (Skelly *et al.* 2005), and removal of trees from historically open-canopy ponds has been proposed as a management intervention for recovery of open-habitat species (Thurgate & Pechmann 2007). Conversely, canopy cover can be increased at targeted breeding sites to alleviate mortality linked to high temperature. Similar strategies have been used to assist reptiles, including deployment of shade cloth (Mitchell *et al.* 2008) and vegetation restoration to lower nest temperatures (Hansen *et al.* 2010).

The cool, moist conditions of riparian microclimates (Ryken, Chan & Moldenke 2007) can be maintained by riparian buffers (Brosofske *et al.* 1997) including adjacent forest reserves as narrow as 6 m wide (Anderson, Larson & Chan 2007). At the landscape scale, topographical variation provides shade that affects shelter microclimate conditions. Habitat modelling for the Siskiyou Mountains salamander *Plethodon stormi* suggested that suitable conditions are found on the 'dark side' of ridgelines (Reilly *et al.* 2009). Sites selected for long-term management in Oregon, USA, were located in habitat known to retain cool, moist conditions, including rocky substrates, areas with canopy cover, and north-facing aspects with hill shading (Olson *et al.* 2009).

Enhancement and restoration of breeding sites

A major challenge will be to alleviate reproductive failure and promote survival of amphibians under uncertain or altered rainfall regimes. Experimental manipulations of breeding habitat can provide some guidance in this regard but few successful cases have been documented (Rannap, Lohmus & Briggs 2009) and limited information is available for some reproductive modes. Heterogeneous aquatic breeding sites that vary in size and depth can buffer amphibian populations from environmental stressors and enhance population persistence (Denton *et al.* 1997; Semlitsch 2002; Rannap, Lohmus & Briggs 2009). Creating 5–10 diverse wetland habitats along a hydrologic continuum can reduce catastrophic mortality associated with drought, pathogen outbreaks, and predation on early life-history stages (Petranka *et al.* 2007). Restoration of breeding habitat complexes may rapidly increase population size

of threatened species (Rannap, Lohmus & Briggs 2009). However, wetland dynamics are complex, and the success of restoration efforts will be mediated by factors such as vegetation, geomorphology, and drought (De Steven & Toner 2004; De Steven *et al.* 2006). Further, designs that include permanent ponds can promote establishment of non-target species such as the American bullfrog *Lithobates catesbeianus* and predatory fish (Maret, Snyder & Collins 2006; Hartel *et al.* 2007); these non-target species can compromise the intended goals of the project. Complex designs that include diverse habitats may compensate for the fact that functional pond hydrology required for larval development and exclusion of predatory fish can be difficult to mimic (Biebighauser 2007; Gamble & Mitsch 2009; Korfel *et al.* 2010). Heterogeneous landscapes in boreal farmlands of southern Finland lower the risk of regional population declines of the common frog *Rana temporaria* under extreme weather perturbations and promote recovery in post-disturbance phases (Piha *et al.* 2007). Local programmes can be scaled up into large country-wide initiatives. The pond project for rare amphibian species in Denmark (Fog 1997), the Million Ponds Project in the UK and the LIFE project in the eastern Baltic aim to reverse historical pond loss by creating an extensive network of new countryside ponds, targeting focal species.

Similarly, for phytotelm or bromeliad-associated amphibians, supplementing arboreal breeding sites can serve to bolster populations. Donnelly (1989) artificially increased bromeliad availability, tadpole-rearing sites for the strawberry poison-dart frog (*Oophaga pumilio*, formerly *Dendrobates*). Increased male survival and immigration of females resulted. Artificial structures such as tadpole-rearing cups attached to tree trunks in wet tropical forest are also utilized by this species (Stynoski 2009).

All such manipulations that increase connectivity between populations have the potential to increase the spread of pathogens such as the amphibian chytrid fungus (Hess 1996). This presents a conundrum for managers that will need to balance benefits of connectivity in enhancing demographic processes against risk of disease-induced extinction (Gog, Woodroffe & Swinton 2002; McCallum & Dobson 2002).

Manipulation of hydroperiod or water levels at breeding sites

Targeted intervention may be required to retain functional natural breeding sites (Semlitsch 2002; Seigel, Dinsmore & Richter 2006). Since aquatic breeding amphibians require minimum hydroperiods to reach metamorphosis, beneficial interventions may consist of artificial extension of hydroperiods, including irrigation, filling drainage ditches, and managing evapotranspiration through vegetation manipulation.

Retention, restoration, and creation of lentic wetland and bog complexes are management actions in the US Conservation Assessment for the Oregon spotted frog *Rana pretiosa* (Cushman & Pearl 2007). In Oregon, these actions include (i) vegetation management at constructed ponds; (ii) pond creation through irrigation ditch segmentation; (iii) reconstruction

of a river weir to retain water in a marsh; (iv) pond excavation to enhance water retention; and (v) reestablishment of dam building activity of the North American beaver *Castor canadensis* to promote water retention (C. Pearl, US Geological Survey, Corvallis, OR; pers. comm.).

Stream populations may similarly be enhanced by modifying flow and providing stable, complex breeding habitats. Maintaining or restoring channels with shapes that provide stable habitat can prevent desiccation of eggs in dry years and scouring of substrate in wet years (Kupferberg 1996). The foothill yellow-legged frog *Rana boylei* in northwestern California, USA, is known to respond positively to 'bank feathering' restoration, which includes removal of levee-like features and encroaching riparian vegetation to re-establish low water-velocity habitats (Lind, Welsh & Wilson 1996).

In the arid USA southwest, wind- and solar-powered pumps have been used since 1992 to retain water levels in constructed and earthen stock ponds, drawing upon groundwater resources not otherwise accessible during dry periods (Fig. 1). These wetlands have been essential in maintaining a variety of wildlife including the threatened Chiricahua leopard frog *Lithobates chiricahuensis* on private ranch land in New Mexico (Turner Ranch Properties, L.P.; M. Christman, US Fish and Wildlife Service, Albuquerque, NM; C. Kruse, Turner Enterprises, Inc.; pers. comm.). In 1992, this frog was known from only one location in this drainage. By 1995, the species had colonized all earthen tanks and some steel tanks with vegetation allowing frogs to enter tanks; today this is the largest, healthiest population of Chiricahua leopard frogs in New Mexico.

Concluding thoughts

Climate change is recognized as a major threat to amphibian biodiversity and has already contributed to the listing of some species in the World Conservation Union (IUCN) Red List (Hero *et al.* 2006). The Amphibian Conservation Action Plan identifies gaps in scientific knowledge and general management actions for amphibians in response to climate change (Gascon *et al.* 2007). Despite this, there are surprisingly few examples where specific actions to address climate change impacts have been incorporated into local or regional management plans, programmes and activities for amphibians. We believe that improved knowledge of the feasibility and

effectiveness of specific actions will be critical in fast-tracking progress in the application of general adaptation management principles. Given the pressing nature of the problem, it is sensible to target such effort toward high-risk areas and species (Lawler *et al.* 2009; Blaustein *et al.* 2010) as well as locations where species are most likely to persist or migrate to under climate change (e.g. cool or stable wet environments, Killeen *et al.* 2007; Klein *et al.* 2009; Reilly *et al.* 2009; Shoo *et al.* 2010, 2011).

The amphibian chytrid fungus is also recognized as a major threat to frog populations worldwide (Skerratt *et al.* 2007), but the role of climate change in current chytrid related extinctions is contested (Pounds *et al.* 2006; Rohr *et al.* 2008). Given that the growth and impact of chytrid infections is strongly temperature-related (Berger *et al.* 2004) it is highly likely that climate change will increase future impacts in some areas, whilst reducing them elsewhere. Protection of climate refuges, where environmental conditions prevent disease outbreaks, can therefore assist some species (Puschendorf *et al.* 2009). Functional trait models (Kearney *et al.* 2010) have the potential to inform where microhabitat manipulations might be adopted to reduce chytrid transmission under future climate scenarios.

We have described some innovative local-scale actions designed to minimize loss of amphibians at risk. The challenge now for conservation researchers and managers is to cooperate and test, monitor and iteratively update the growing store of effective management interventions. Only then will general principles translate into management tools for amphibian protection. To enhance communication, we have established a web portal to compile practical conservation actions within strategic areas (<http://www.parcplace.org>). This compilation initially focused on stop-gap measures used to save the rarest species, including head-starting, captive breeding, and translocation efforts. We aim to expand upon this internet resource to communicate current and tested technological innovations that may aid in amphibian conservation management under climate change.

Author contributions

J-M.H. secured funding and hosted the workshop. L.P.S. wrote the paper. All other authors contributed to the workshop and in some cases helped to develop the manuscript.

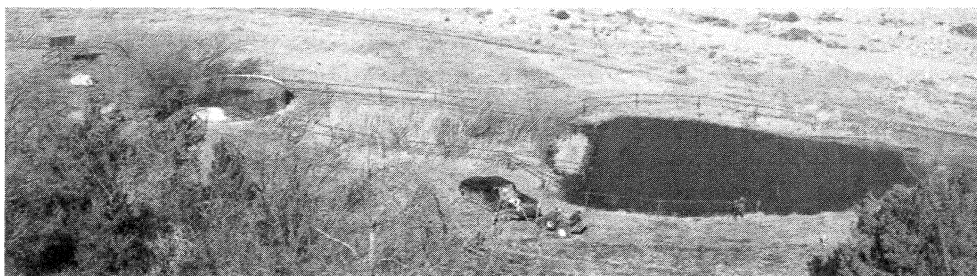


Fig. 1. Windmill- and solar-powered pump installed to retain water levels in ponds (Turner Ranch Properties, L.P.; M. Christman, US Fish and Wildlife Service, Albuquerque, NM; photograph: C. Kruse, Turner Enterprises, Inc.; pers. comm.).

Conflict of interest

The authors declare no conflict of interest.

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