Local habitat restoration in streams: Constraints on the effectiveness of restoration for stream biota

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Summary The restoration of physical habitat has emerged as a key activity for managers charged with reversing the damage done by humans to streams and rivers, and there has been a great expenditure of time, money and other resources on habitat restoration projects. Most restoration projects appear to assume that the creation of habitat is the key to restoring the biota ('the field of dreams hypothesis'). However, in many streams where new habitat is clearly required if populations and communities are to be restored, there may be numerous other factors that cause the expected link between habitat and biotic restoration to break down. We discuss five issues that are likely to have a direct bearing on the success, or perceived success of local habitat restoration projects in streams: (i) barriers to colonization, (ii) temporal shifts in habitat use, (iii) introduced species, (iv) long-term and large-scale processes, and (v) inappropriate scales of restoration. The purpose of the study was primarily to alert ecologists and managers involved in stream habitat restoration to the potential impacts of these issues on restoration success. Furthermore, the study highlights the opportunities provided by habitat restoration for learning how the factors we discuss affect populations, communities and ecosystems.

Key words *dispersal barriers, field of dreams, habitat structure, introduced species, restoration ecology, scale.*

Introduction

There has been a concerted effort in recent years to begin reversing the tremendous damage that has been exacted on freshwater ecosystems by human beings. Much of this effort has been targeted at restoring physical habitat, on the presumption that this will engender a desirable ecological response (Palmer *et al.* 1997; Lake 2001b). Coined the 'field of dreams hypothesis' (Palmer *et al.* 1997) (i.e. 'if you build it, they will come'), this approach is implicitly based on the observation that in many ecological systems, biotic diversity is positively correlated with habitat heterogeneity (Bell *et al.* 1991; Rosenzweig 1995).

Arguably, because habitat heterogeneity has been lost in so many aquatic systems as a result of both instream (e.g. desnagging, dredging and straightening) and riparian zone activities (e.g. vegetation removal), there is good reason to believe that a lack of habitat is an important aspect of the overall degradation that has occurred. Consequently, if this damage is to be reversed, the repair and creation of depleted habitat will be a necessary component of restoration. However, as pointed out in a number of reviews (Frissell & Nawa 1992; Kauffman *et al.* 1997; Roni *et al.* 2002), local habitat manipulations may be necessary, but not sufficient, to restore key aspects of ecosystem structure and function – a fact exemplified by several recent meta-analyses (Smokorowski *et al.* 1998; Larson *et al.* 2001). For example, in a recent review (Smokorowski *et al.* 1998) of 78 habitat rehabilitation (or enhancement) projects targeting increases in riverine and wetland fish populations, just four (5% of the 55 completed projects) were able to demonstrate an increase in fish production, even though 98% achieved their habitat targets. Low success rates in achieving biological targets have also been reported by Beschta (1994) and Larson *et al.* 2001) for fish and invertebrate fauna, respectively.

In addition to the apparently low success rate, few attempts at habitat restoration are properly evaluated to determine either their success or reasons for their failure (Lake 2001a). Among those that are evaluated, few meet the basic design principles that allow a thorough scientific and statistical assessment (Chapman & Underwood 2000; Downes *et al.* 2002). Others are evaluated only over short time scales due to budgetary constraints (Osborne *et al.* 1993), and thus cannot accommodate lag effects in the response of the biota. Hence, very few restoration attempts actually contribute significantly to our knowledge about how to go about stream restoration successfully (Minns *et al.* 1996; Michener 1997; Smokorowski *et al.* 1998; Chapman & Underwood 2000). Clearly, this situation must be reversed if restoration ecology is to grow as a science (Hobbs & Norton 1996; Lake 2001a).

The conceptual aspects of stream restoration (goal setting, monitoring, methodologies, etc.) have been discussed in the literature, and several strategies for setting priorities and planning restoration programs have been proposed (e.g. Hobbs & Norton 1996; Lake 2001b; Roni *et al.* 2002). There has, however, been much less consideration of the ecological processes (e.g. dispersal, recruitment, species interactions, etc.) at work as a system responds to physical habitat manipulation, and importantly, how these factors might limit the biotic response to any physical changes. While there are many such factors that could be identified, here we discuss five broad issues: (i) barriers to dispersal of biota, (ii) temporal changes in habitat use, (iii) introduced species, (iv) long-term or large-scale driving processes, and (v) inappropriate scales of restoration (Table 1), that together encompass many of the more important factors that will influence the biotic response following restoration, potentially causing restoration to fail (or be perceived to fail) in achieving desired ecological goals.

In applying habitat restoration in streams, it seems that most of these issues are commonly overlooked; a problem that we suspect comes in part from failing to consider localized habitat restoration within a broader spatial and temporal context (or scope). We therefore close by highlighting the potential for insights gained from landscape ecology, which examines regional processes, to provide valuable information for planning and guiding restoration.

While we focus our attention on streams and rivers, the points made may apply equally to other ecological systems (both aquatic and terrestrial) in which habitat is restored locally in order to seek a biotic response. It should be stressed that despite the problems that can beset habitat restoration, we do not believe that habitat restoration is unnecessary; this is far from the case. What we do suggest is that habitat modifications will likely meet with higher success rates, and the causes of failure be more readily identified when the factors we discuss are considered.

Barriers to colonization

In the absence of active introductions, colonization of restored habitat is entirely reliant on the dispersal of organisms from extant populations. Even where local populations still exist, dispersal can still be important. For example, Riley and Fausch (1995) found that 2 years on from habitat restoration, dispersal, rather than greater survival or recruitment, was responsible for increases in abundance of three species of salmonid, even though each species was initially present at restored sites.

Rates of colonization will generally depend largely on the distance between the restored areas and potential source populations (Kareiva 1990) as well as the dispersal abilities of the relevant species (Skalski & Gilliam 2000). For many riverine organisms, dispersal is constrained to movements along the stream channel, making longitudinal connectivity critical (Wiens 2002), while at the same time dramatically increasing travel distances far beyond the overland or straight line distance between points within a stream network (Fagan 2002). Despite famous examples of individuals of some taxa dispersing over huge distances (e.g. tagged Golden Perch *Macquaria ambigua* (Richardson) have been recaptured thousands of kilometers away from their release point; Koehn & O'Connor 1990), it is clear that such long range movements are relatively rare, and that individuals of most taxa move only short distances over their lifetime (Bunn & Hughes 1997; Rodriguez 2002). This immediately constrains the probability that restored habitat will be colonized, particularly in the short term.

In addition, in many catchments connectivity of stream networks has been lost due to instream barriers, thereby constraining the likelihood of colonization even further (Ward & Stanford 1995; Stanford *et al.* 1996). We distinguish here between 'hard' and 'soft' barriers to connectivity. Hard barriers represent actual physical structures such as dams and weirs that block the channel, thereby making dispersal physically impossible without human intervention, particularly in an upstream direction (Ward & Stanford 1995). The installation of fish ladders is one way in which this type of barrier is being overcome, but this is of little help to most taxa (including some fish) with low mobilities (Harris 1984; Jungwirth 1996). There is the additional problem that in large reservoirs, the ability of animals to find their way is lost in the absence of any directional flow (McCully 1996). Perhaps the best example of this comes from rivers such as the Columbia River in North America, where juvenile salmon are transported across large dams each year in the holds of barges so that they can make their migration to sea (Maule *et al.* 1988).

Soft barriers are associated with the isolation of restored habitat, whether this is through the sheer distance from potential source populations (e.g. Fuchs & Statzner 1990; Lafferty *et al.* 1999), or because intervening stream sections present conditions through which organisms are unlikely to disperse, even when within their dispersal range. There is, for example, a number of studies demonstrating that the

Table 1. **Important ecological questions to consider in the planning and target setting stages of habitat restoration**

1. Are there barriers to colonization?
    - What and where are the source populations?
    - How can potential barriers be overcome?
2. Do the target species have particular habitat requirements at different life stages?
    - What are these requirements?
    - How should these habitats be arranged spatially?
3. Are there introduced species that may benefit disproportionately to native species from habitat restoration?
    - Can colonization of these organisms be restricted?
4. How are long-term and large-scale phenomena likely to influence the likelihood, or timeframe of responses?
    - Will these affect the endpoints or just the timeframe of responses?
    - How will this affect monitoring strategies, and can monitoring strategies be adjusted to deal with this?
5. What size habitat patches must be created for populations, communities and ecosystem functions to be restored?
    - Is there a minimum area required?
    - Will the spatial arrangement of habitat affect this (e.g. through the outcomes of competition and predation)?

movements of pool-dwelling fish are enhanced when intervening habitats are shorter (Lonzarich *et al.* 2000), deeper (Gilliam & Fraser 2001), or have lower velocities (Schaefer 2001). It is worth noting that high flows may also play a key role in overcoming both hard and soft barriers, both by passively redistributing organisms and by inundating physical 'hard' barriers to active movement (Harris 1984; Unmack 2001).

The movement of organisms, both actively and passively, is also influenced by channel complexity and the distribution of habitat patches (Bond *et al.* 2000; Kling *et al.* 2000; Gilliam & Fraser 2001). In their modelling of how metapopulations respond to habitat addition in terrestrial systems, Huxel and Hastings (1999) found that restoring habitat close to remaining source populations could significantly reduce the time lag of response when compared to restoration of habitat patches at random. This seems intuitive for terrestrial and aquatic systems alike, but field-testing these predictions is yet to be done.

The effects of soft barriers are not restricted to instream dispersal. Patterns of terrestrial dispersal by adult insects (most of whom are weak flyers) will be affected by patterns of air movement (Baldwin *et al.* 1975; Downes & Keough 1998). For these taxa, instream habitat restoration may require similar action outside of the channel if population dynamics are to be fully restored.

Temporal changes in habitat use

In general, habitat restoration efforts (particularly, for example, those associated with fish) are based largely on the restoration of what is believed to be good habitat for a particular (usually adult) life-stage, without considering the age at which demographic processes are most limiting. There are good examples in which lack of habitat for a particular life-stage causes significant population bottlenecks (e.g. Beck 1995), but the importance of such habitats is not always obvious. For example, local abundances of semiaquatic insects may depend more on factors affecting the adults, such as the availability of suitable oviposition sites (Peckarsky *et al.* 2000; Speirs *et al.* 2000; Reich in press) than on the specific characteristics of either juvenile or adult habitat, but these issues are poorly understood. Other taxa undergo short- and/or long-range movements (e.g. to spawn), or utilize distinct habitats as juveniles and adults (Kocik & Ferreri 1998), in which case spatially isolated habitats may require concurrent restoration (habitat complementation; Schlosser 1995), and be free of the types of barriers discussed above.

As well as ontogenic habitat shifts, many species utilize novel habitats (refugia) during periods of environmental stress such as floods and droughts (ecological disturbances; Sedell *et al.* 1990; Schlosser 1995). For example in lowland stream systems that intermittently are dry, organisms must disperse into, or local residents survive within, the few remaining pools if populations are to persist (Schlosser 1995; Labbe & Fausch 2000; Lake 2003). There are strong parallels here with ontogenic habitat shifts (Sedell *et al.* 1990), but because disturbances are often infrequent and unpredictable, these intermittent refugia may be substantially more difficult to identify, or may have been lost from the system altogether because of human activities. Similarly, in streams subjected to large variations in discharge, identifying, protecting and attempting to restore refuge habitats used by the biota should be an important consideration in restoration, even where, on average, other habitat modifications appear successful.

Introduced species

For many of the invasive species in our waterways, little is actually known about how they interact with native plants and animals. There are some well-documented examples in which exotic species have responded rapidly to habitat restoration, out-competing native biota (Zedler 2000; Klotzli & Grootjans 2001). For example, the highly invasive plant Purple Loosestrife (*Lythrum salicaria* Linnaeus) has come to dominate many restored wetlands and stream margins in parts of North America (Cole 1999). Even in the absence of strong evidence for negative interactions, many invasive species (almost by definition) display traits that favour them taking advantage of newly created habitat (Rejmanek 2000). Thus, the arrival of exotic before native species might indicate some degree of success (D. Crook, pers. comm., 2001) because habitat has clearly been created. The challenge then is to determine whether habitat restoration can occur in such a way as to favour native over exotic taxa. One example, coming from our own work, is the creation of scour pools (through the introduction of coarse woody debris) in several lowland streams from which habitat has been lost following the formation of erosion-induced sand slugs (Davis & Finlayson 2000). Despite initial disappointment at the small size of the pools that were formed, these have been colonized by small native fish Mountain Galaxias (*Galaxias olidus* Gunther), but are too small to support a larger-bodied exotic invader Common Carp (*Cyprinus carpio* Linnaeus), which is common within larger pools in unsanded sections of these streams. This example represents simple good luck, but, in general, preventing exotic invasions of newly created habitat is a clear challenge in stream habitat restoration.

Long-term and large-scale processes

Above all else, it is important to place localized habitat restoration within the context of appropriate scales of space and time. In space, most degradation has occurred across large areas of the landscape, often whole catchments. Yet most efforts at habitat restoration are pitched at much smaller scales, typically individual sites or stream reaches. As a consequence, the legacies of past disturbances and the impacts of on-going disturbances operating at larger (possibly catchment-wide) scales can compromise works done at individual sites or reaches. One example would be efforts to restore habitat in rivers affected by large dams, where altered flow regimes may override the benefits of restoring habitat such as large woody debris. The central problem is that habitat restoration is, with few exceptions, limited to small spatial scales because of logistical and resource constraints, and because ecological values must be balanced with the economic and social values derived from ongoing human pursuits. However, if broad-scale disturbances that, as historic, ongoing or impending processes, are likely to influence the outcomes of localized habitat-restoration, then this must be addressed early in the planning phase of restoration. Bohn and Kershner (2002) provide an excellent example in which declines in populations of Bull Trout (*Salvelinus confluentus* (Suckley)) and Cutthroat Trout (*Oncorhynchus clarki lewisi* Suckley) were initially believed to result from a lack of suitable habitat, but were ultimately linked to sediment inputs to the stream network, which were occurring throughout the catchment. Thus, a watershed analysis directed initial management actions toward minimizing sediment inputs from outside of the stream, rather than tackling the issue of habitat limitation directly, thereby changing the nature and timing of management actions that were adopted in addressing observed fish declines. Ecological goals and endpoints set within this broader context will perhaps become less ambitious and the necessary management actions perhaps more difficult to achieve, but in the longer term such an approach may be far more effective.

As with broad-scale spatial processes, temporal trends in processes such as rainfall can have significant consequences for restoration, particularly at the short (< 10 years) time scales over which outcomes from restoration are typically sought. Both floods and droughts affect population processes such as mortality and recruitment, and thus can slow rates of population growth and increase the frequency of localized extinctions. This, combined with other rate-limiting factors, such as dispersal, will mean that population, community and ecosystem responses to the addition of habitat will often take considerable lengths of time (Mitsch & Wilson 1996; Lake 2001b). Of course, these sorts of delays do not cause restoration to fail, but instead, may push response times beyond those over which monitoring is typically funded.

In the longer term, phenomena such as global warming and species invasions will potentially cause significant directed changes in aquatic ecosystems (Sala *et al.* 2000), and this may require the resetting of restoration targets for both community structure and ecosystem function. Dealing effectively with large-scale spatial and temporal processes in localized restoration efforts will require a great deal of effort, in the planning phase of restoration, to determine realistic goals and realistic timeframes over which these goals might be reached (Hobbs & Norton 1996; Lake 2001a).

Inappropriate scales of restoration

The spatial extent of restoration is rarely set from the perspective of target species or communities, instead being driven more often by human perceptions of important scales, or by issues of economic and social convenience. This type of scoping problem (Schneider 1994) can result in great mismatches between the requirements of individual animals (in terms of foraging behaviour, home range size, etc.), and the areas of habitat that are actually created (Minns *et al.* 1996). Yet for many species the viability of local populations is highly contingent on patch size (Dunham & Rieman 1999; Sand-Jensen *et al.* 1999). Therefore, even if we restore the correct types of habitat, doing so at the wrong scale can cause restoration to fail, and at the same time cause potentially useful restoration techniques to be abandoned. Although there appears to have been no direct research into the importance of habitat-patch size in the stream restoration literature, evidence from studies examining habitat fragmentation suggests this is an important issue to consider (Dunham & Rieman 1999; Harig & Fausch 2002).

There are some physical properties of streams such as water temperature and rates of nutrient uptake for which these scaling rules are better understood. For example, Storey & Cowley (1997) found that in three second-order streams in New Zealand, water temperature began to stabilize only after passing through several hundred meters of vegetated riparian zone. Nutrient levels required double this distance. Similar predictions come from the theoretical work of Collier *et al.* (1998). Unfortunately, however, these scaling issues are generally much less tangible because the spatial scales of environmental pattern to which different organisms respond are poorly understood (MacNally 1999). Thus, while the question of patch-size can be reconciled for some physical properties of streams and for taxa about which we know sufficient biology (including home-range size, dispersal ability, etc.), a concerted effort should be made to include these questions in future restoration experiments.

Another critical question is how the effects of large-scale processes on ecological communities (see previous section) are mitigated as the size of the area being restored is enlarged. Finally, a number of authors (Minns *et al.* 1996; Bell *et al.* 1997; Palmer *et al.* 1997; Collier *et al.* 1998) have stressed the need to better understand how the spatial arrangement of restored areas will affect the response in terms of rates of recolonization as well as aspects of ecosystem structure and function.

Conclusions

There is no question that the reversal of habitat loss must form an important component of ecological restoration. What is clear though, is that there are a number of factors, other than the presence of habitat, which can influence local population dynamics, and these may operate at different scales in space and time. Successful restoration will only occur where these factors are considered in unison.

At the most basic level, the key issues we have discussed should be considered early in the planning and goal setting stages of restoration, and framed as simple questions, as in Table 1, and potentially incorporated into a more holistic framework such as that proposed by Roni *et al.* (2002). In some cases the answers to these questions will highlight important knowledge gaps. Where this is the case, the necessary information should be gathered before full-scale restoration begins (e.g. through pilot studies), or the restoration and monitoring strategy modified so that relevant questions can be tested explicitly. These aspects of planning could greatly increase the rate at which we learn how to best restore.

At a more general level, however, we concur with the idea that progress in restoration can be maximized through linkages to landscape ecology (Schlosser 1991, 1995; Bell *et al.* 1997). Although described in many ways, landscape ecology has two important foci: pattern (e.g., habitat patch structure in the landscape), and process (e.g. recruitment and dispersal), and how these factors interact (Wiens 2002). The first of these (pattern) has obvious consequences for habitat restoration because habitat creation represents a direct manipulation of landscape structure. Process in this case is concerned with issues such as dispersal, colonization and local extinction, which drive the responses to restoration. Thus, there are strong parallels between the questions of interest to landscape and restoration ecologists alike, and many lessons that might be learned from taking a landscape perspective (Bell *et al.* 1997; Fausch *et al.* 2002). In return, restoration provides unique opportunities to manipulate habitat across large spatial scales. The similarities and cross-benefits of these two fields are being increasingly recognized – for example, in the shift toward watershed, or whole catchment, restoration (Roni *et al.* 2002). It is our hope that as this occurs, there will be growth in the opportunities and support for research and experiments of the sort that will aid our understanding and ability to deal with some of the limits on habitat restoration outcomes highlighted here.

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