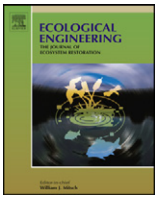
Ecological Engineering 37 (2011) 1379–1386

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



An outcome-based model for predicting recovery pathways in restored ecosystems: The Recovery Cascade Model

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ARTICLE INFO

Article history:
Received 22 October 2010
Received in revised form 23 March 2011
Accepted 27 March 2011
Available online 6 May 2011

Keywords:
Ecosystem rehabilitation
Ecosystem services
Environmental flow
Recovery trajectory
Restoration ecology
River restoration
State-and-transition

ABSTRACT

Restoration is increasingly the focus of ecosystem management. Few conceptual models exist for predicting the consequences of restoration, especially those that predict the stages of recovery following restoration. Existing models focus either on defining endpoints for recovery or on defining ecosystem processes, but often do not identify barriers to recovery or potential negative effects of restoration. We describe a conceptual model that identifies the outcomes of the recovery pathways following flow restoration in rivers: the Recovery Cascade Model. The model identifies six general aspects of recovery following restoration: physical ecosystem change; creation of, or improvement in habitat condition; reconnection of the restored area to adjacent ecosystems; recolonization of the restored area; resumption of ecological processes; re-establishment of biotic interactions and reproduction by colonists in the restored area. These aspects may occur in sequence, such that recovery is blocked by a single barrier. The model accommodates feedback loops and includes strong connections between physical processes and ecosystem processes, but also identifies factors that are important in achieving endpoints such as potential barriers to further recovery. Identification of barriers to recovery enables improved planning to maximise the positive effects of restoration. By focussing on outcomes, the model provides a planning tool for managers that can be adapted for different ecosystems and restoration methods and which can be used to identify the amenities that an ecosystem will deliver at different stages of recovery. Ecosystem recovery is as much about overcoming barriers as it is about restorative actions.

1. Introduction

Restoration is increasingly the focus of ecosystem management. Few conceptual models exist for predicting the consequences of restoration, especially those that predict the stages through which an ecosystem will pass (the pathway) as it develops following restoration. Identifying pathways is important because in doing so, barriers to reaching the desired restoration endpoint may be identified ahead of time and ameliorated. In addition, various stages in a post-restoration pathway may be bottlenecks or have negative effects on aspects of the system, about which managers need to be forewarned (Hughes et al., 2005). Determining recovery trajectories may also allow for landscape-scale and long-term ecological and biophysical processes to be accommodated (Hughes et al., 2005; Spink et al., 2009). There is therefore a need for outcome-based models that identify the pathways followed by ecosystems after restoration. Here we describe the Recovery Cascade Model, comprised of six aspects of ecosystem recovery: physical ecosystem change; creation of, or improvement in habitat condition; reconnection of the restored area to adjacent ecosystems; recolonization of the restored area; resumption of ecological processes; re-establishment of biotic interactions and reproduction by colonists. It is based on an analysis of recovery in restored river systems, can also be used to identify barriers to recovery and the amenities that an ecosystem will deliver at different stages of the recovery trajectory.

2. Conceptual models of ecosystem recovery

Few conceptual models exist for predicting the consequences of restoration partly because it is difficult to make specific predictions regarding either the stages or the endpoint of recovery pathways (Choi, 2004; Hobbs and Cramer, 2008). Choi (2004) concludes that because predictive abilities are limited, expectations of endpoints for restoration must be ‘realistic’. In an outcome-based model, this realism takes the form of subsuming specific ecological processes

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doi:10.1016/j.ecoleng.2011.03.015

and events into general stages in the recovery pathway. These processes and events are described in a very general way and may take different forms. The range of outcomes that may arise from these events are described and the focus is on the impact this will have on further development of the recovery pathway rather than on describing the composition of the ecosystem at each stage. These models are therefore dynamic (as identified by Hobbs and Norton, 1996) and avoid comparison with reference sites.

Reference sites are problematic to identify in many landscapes (e.g. Zedler and Callaway, 1999; Martin and Kirkman, 2009), but are useful for assessing whether (or which) endpoints are reached (Choi, 2004). However, as presently conceived they do not assist in determining recovery pathways or the impediments thereto. Defining reference condition is increasingly problematic in the context of rapid environmental change and the possibility of a 'no-analogue future' (Hobbs and Cramer, 2008). Therefore, the use of this type of outcome-based model is not dependent on defining reference condition or using reference sites.

Existing conceptual models for ecosystem recovery tend to be either endpoint models or process-based models. Endpoint models define the desired endpoint after restoration and may be at least partly aspirational (Hillman and Brierley, 2005; Fryirs and Brierley, 2009). Having a clearly defined guiding image (leitbild), goal or endpoint is one of the five criteria for ecologically successful river restoration (Palmer et al., 2005), and is important in attempts at the restoration of any ecosystem (Choi, 2004), but there are few detailed models for endpoints that are articulated in the literature (but see examples in Hillman and Brierley, 2005). An example is the 'Living River' Model for the River Meuse in France where small-scale trials of habitat restoration proved successful in supporting threatened species, and the model emphasised improved connectivity along the river, which was expected to improve biodiversity (Pedroli et al., 2002). Other endpoint models are not so ambitious. For example, the large experimental flood in the Colorado River, USA in 1996 had endpoint goals of restoring beaches for recreational activity, controlling exotic vegetation, deepening the channel and restoring backwater habitats (Collier et al., 1997; Schmidt et al., 2001). Beach restoration, channel deepening and physical restoration of backwaters were successful with the effects lasting months to years, but the effects on vegetation, fish, invertebrates and algae were limited (Collier et al., 1997; Shannon et al., 2001; Valdez et al., 2001). Endpoint models, therefore, can vary widely in the scope of their objectives: from relatively simple, easily measurable geomorphic changes to long-term ecosystem sustainability (Hillman and Brierley, 2005). While scientific information can indicate what conditions might comprise sustainability and what type of restoration might produce certain outcomes, the determination of what the endpoint should be for restoration involves the whole community and its political processes (Dufour and Piégay, 2009). The guiding image developed for a river might be for an ecologically functioning ecosystem that bears little resemblance to pristine or reference conditions.

Process-based models for restoration are based on the idea that natural disturbance regimes structure ecosystems and disruption to these regimes is the main cause of anthropogenic disturbance (Trowbridge, 2007). This idea is particularly strong among those working on freshwater ecosystems (e.g. Poff et al., 1997) but there is evidence from many ecosystem types (e.g. Martin and Kirkman, 2009). Underlying this idea is the 'field of dreams' hypothesis that implies very strong physical connections between physical processes and ecosystem processes (Palmer et al., 1997; Hilderbrand et al., 2005; Trowbridge, 2007). There is good evidence for this connection in many ecosystems (e.g. Martin and Kirkman, 2009) but ecology has moved beyond deterministic concepts of community assembly to discussion of concepts of thresholds, historical contingency and ecological filters (Trowbridge, 2007; Martin and Kirkman, 2009). However, evidence from the successful restoration of herbaceous wetlands in oak-dominated systems shows that thresholds between alternative states may be crossed by management intervention (Martin and Kirkman, 2009).

Process-based models are sometimes implicit in the decision to undertake restoration for a particular objective. However, there are a series of events that must occur in an ecosystem between a restoration activity and the desired outcome. For example, an objective to increase waterbird breeding may require floodplain inundation, followed by the re-assembly of an aquatic floodplain food web that can support the energy requirements of breeding birds. That is, the food web must be reassembled in order to support this high-energy activity. In addition, the birds must be able to locate the flooded area—that is, they must exist in the nearby landscape so that they can respond to the flooding trigger. This is an example of the need for a physical process (inundation) to initiate ecosystem processes (food web assembly). There is (at least) one threshold state to cross to achieve the endpoint (sufficient food web productivity to support waterbirds) and there is (at least) one filter in operation (bird presence in the landscape) that may determine success.

A challenge for restoration practitioners exists in the potential for alternative stable states for ecosystems to result from the same restoration action at different places or times (Hilderbrand et al., 2005; Hughes et al., 2005; Trowbridge, 2007). Indeed, recognizing and incorporating uncertainty into models for ecosystem recovery is important for successful restoration (Hilderbrand et al., 2005; Hughes et al., 2005). Models based on physical and ecological processes do not necessarily inform ecosystem managers of the outcome of a sequence of processes for ecosystem services or other aspects of human amenity. They also do not necessarily identify barriers to successful ecosystem change. Outcome-based models therefore offer environmental managers planning to carry out ecosystem restoration a more integrated but less deterministic method of decision support.

Some general models for recovery pathways have been identified: recovery that follows the path of degradation, but in reverse order (the 'carbon copy myth', Hilderbrand et al., 2005); recovery that shows hysteresis; recovery but to an endpoint that differs from the pre-degraded state (Humpty Dumpty Model); and recovery where the endpoint is dependent on stochasticity in the trajectory itself (Sarr, 2002; Lake et al., 2007). Recovery pathway models for particular ecosystems tend to take one of two forms: a matrix-style model involving a combination of different pre-restoration factors (e.g. Lunt et al., 2007; Benscoter and Vitt, 2008) or a series of stepwise changes at which different factors operate (e.g. Grant, 2006; Robson et al., 2009). Matrix-style models generally focus on ecosystem processes rather than outcomes and are effectively the process-based models described above, but designed to identify or describe pathways of ecosystem recovery. In contrast, Grant's (2006) state-and-transition model focuses on outcomes because the forest ecosystems resulting from restoration following bauxite mining must comply with pre-determined requirements. In this case, different ecosystem states arise from similar restoration procedures and these states represent more or less desirable outcomes (Grant, 2006). Grant's model demonstrates how a reference state may be included, identifies desirable and undesirable ecosystem change and when management intervention will be necessary to divert undesirable processes and avoid poor outcomes. It identifies a series of stepwise changes in the ecosystem as the recovery pathway develops, with a number of thresholds and filters and a range of ecosystem condition at any one stage of the pathway. It is also designed so that managers can identify indicators of desirable or undesirable conditions that may act as triggers for further inter-