Riparian vegetation – degraded, invaded, transformed. Towards a conceptual framework for management

David M. Richardson
Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University,
Private Bag X1, Matieland 7602, South Africa

Summary In most parts of the world, riparian zones (the fringes of rivers and streams) are highly modified, with radically changed composition and functioning. Alterations caused by alien plants, or environmental changes that facilitate shifts in dominance creating novel ecosystems, are often important agents of perturbation in these systems. Many restoration projects are underway. Objective frameworks based on an understanding of biogeographic processes at different spatial scales (reach, segment, catchment), the specific relationships between invasive plants and resilience and ecosystem functioning and realistic endpoints are needed to guide sustainable restoration initiatives. This paper examines the biogeography and the determinants of composition and structure of riparian vegetation in temperate and subtropical regions and conceptualises the components of resilience in these systems. Pervasive human-mediated changes to multiple factors in riparian environments demand innovative approaches to restoration.

The conceptual framework for restoration of riparian vegetation defines appropriate management interventions at different spatial scales to deal with the range of factors that influence vegetation recovery and invasibility. The framework has been used to design a decision-making protocol for restoring riparian zones affected by invasive alien plants in South Africa and could guide similar initiatives in other parts of the world.

Keywords Biogeographical processes, biological invasions, conservation biogeography, emerging ecosystems, exotic species, invasive alien species, resilience, restoration.

INTRODUCTION

Riparian zones are the fringes of rivers or streams. They form the interface between aquatic and terrestrial ecosystems, usually occupy small parts of the landscape, but are often the focus of intensive human activity, and present special challenges for managers. Many types of human-mediated disturbances influence riparian ecosystems. Damming and the regulation of flows alter river channel form and the composition and extent of riparian habitat. Logging, grazing and trampling, water extraction, salinisation, recreation and other land uses also affect riparian zones. Such disturbances often occur in concert with, or act as triggers for, plant invasions. There has been a rapid increase in diversity and abundance of alien plants in riparian zones worldwide. Alien plants sometimes have little influence in riparian zones, but they may also bring about radical changes in structure and functioning. Increased abundance or diversity of alien species may also manifest as a symptom of such changes. Major management/restoration initiatives in riparian zones are underway in many parts of the world. Many such operations are carried out without enough thought being given to the full range of factors that potentially influence outcomes. This is becoming increasingly important as climate change is predicted to cause major changes in riparian environments in many parts of the world.

This paper discusses progress towards a conceptual framework for managing/restoring riparian zones based on generalities relating to key ecological processes and the components of resilience in these systems, especially those potentially affected by alien plant invasions.

RIPARIAN VEGETATION – WHAT, WHERE AND WHY?

Riparian zones vary from narrow strips of vegetation along banks of steeply incised streams to wide floodplains adjacent to large rivers that regularly over-top their banks. Wide riparian floodplains of large rivers are not discussed here. The type of vegetation in a riparian zone is determined by the regional climate, the regional pool of species, and the hydrological, geomorphological and disturbance regimes.

Stream classification systems have been developed to assist in conceptualising the various features of rivers at different scales. Most classifications are hierarchical, since the surrounding catchment is important in determining the structure and dynamics of streams. A hierarchical geomorphological model for South African rivers spans the following scales in order of decreasing size: catchment, segment, geomorphological zone, reach, morphological unit and hydraulic biotope.

RIPARIAN VEGETATION: DETERMINANTS OF COMPOSITION AND STRUCTURE

Principles Rivers and streams are dynamic, non-equilibrium ecosystems subject to frequent disturbance events that have a strong influence on the biotic characteristics of riparian communities. Fluvial and hydrological processes are the fundamental determinants of plant distribution patterns in riparian corridors within particular biogeographical regions. New habitat for plant colonisation is provided by the fluvial erosion-deposition process, while hydrology influences the vegetation through floods, droughts and water table fluctuations. Riparian vegetation in many rivers has been adequately characterised by vertical and lateral gradients, reflecting the strong influence of flooding and water availability on species distributions. Riparian plant assemblages typically change continuously. Flooding may physically uproot or damage individuals and inundate areas, causing death or reduced growth. Bank collapse can remove entire plant assemblages, while deposited sediments provide new habitat for colonisation. The attributes of riparian plants are important in determining which lateral zones they occupy and thus the composition and structure of the various riparian plant assemblages. Life-history strategies also determine whether, where, and when a riparian plant species may colonise a site.

Establishment of new (alien) plant species River ecosystems are highly prone to invasion by alien plants, largely because of their dynamic hydrology and because rivers act as conduits for the efficient dispersal of propagules. Once introduced and established in a catchment, many alien plants can exploit conditions by natural flood events and anthropogenic disturbances. Most rivers flow through human settlements, providing multiple opportunities for the introduction of alien propagules into the riparian zone. Rivers are thus 'conveyor belts' that rapidly move propagules, often along with pollutants and large sediment loads, to sites made highly receptive by many types of human-driven modification. Once established, positive feedback mechanisms and considerable propagule pressure can promote the spread of certain plant species at the expense of others via habitat alteration and may result in the development of extensive, dense thickets of alien vegetation in riparian zones.

RIPARIAN VEGETATION – FUNCTIONS AND VALUES

Principles Plant species influence many properties of riparian ecosystems. Through the process of evapotranspiration, riparian plants influence stream flow rates, water levels in the stream aquifer and local climates. Rates of evapotranspiration and of groundwater use vary widely between plant species depending on factors such as rooting depth, leaf area and ability to regulate stomatal conductance. Plants also influence the vertical patterns of moisture in the soil profile. Plant species that develop large (or dense) woody stems can reduce the velocity of flood water and thus increase rates of local groundwater recharge, thereby influencing yet another aspect of the hydrologic cycle. Plants directly and indirectly mediate many nutrient cycling processes. Plants influence rates of sedimentation on the floodplain (depending in part on the amount of biomass present in low strata) and resistance of soils to erosion during flood events (depending in part on root density). Plants with fine, dry fuel loads increase the probability of fire spread in riparian corridors. Plants are also fundamental for sustaining higher trophic levels.

Most riparian ecosystems have high levels of plant diversity and as these levels of diversity change, ecosystem functions can also change. Relationships between plant species diversity and ecosystem function have been quantified for only a few processes (e.g., productivity, decomposition rates). Key questions remain regarding relationships between plant species diversity (or plant functional type diversity) and many riparian ecosystem processes and functions including stream bank stabilisation rate, water purification and various aspects of the hydrologic cycle. For those functions that have been studied, results suggest that the functions decline when species numbers drop below threshold levels.

Many of the conditions created by vegetation processes, such as stabilised stream banks, clean water, diverse animal communities, and recharged water tables, are valued by humans and the corresponding processes that create them have been described as ecosystem functions or ecosystem services. When a valued condition declines, the ecosystem often is considered to be 'degraded'. Typically, however, as riparian vegetation changes, a suite of functions change, often in a complex fashion.

Any change in composition of the plant community will bring about some change in ecosystem function. The dominant species in an ecosystem are most influential; the greatest functional changes occur if the abundance of these species changes. The greater the difference in morphology, growth rate, and other traits between the old and new dominant species (irrespective of whether the new dominant is native or alien), the greater will be the change in function.

Ecosystem function and alien species Because major changes in plant species composition are often

driven by alterations in physical ecosystem processes, it can be difficult to determine causes of the change and to 'ascribe blame'. Is the cause of some functional change the newly dominant (or newly arrived) species, the proximate factors that allowed it to arrive and/or become dominant or some interaction between these factors? Discriminating between 'cause' and 'symptom' is, in some cases, a considerable challenge in the context of alien species and ecosystem degradation. Certain plant species (including many invasive alien species) undoubtedly alter the composition and structure of the vegetation; those that replace indigenous vegetation over substantial areas ('transformers') can change ecosystem function.

RIPARIAN VEGETATION – RESILIENCE DEFINED

Principles Resilience is the ability of an ecosystem to return to its former state following a disturbance or stress, or the time required to return to its former state. The term is often used vaguely, without defining the properties of the ecosystem that could be measured to determine the degree of resilience, or the level of deviation from an acceptable level. Here, resilience is considered in terms of structural/functional composition. Because riparian zones are so dynamic, resilience is difficult to conceptualise in these systems since component species and any defined structure or function are always recovering from disturbance. Most riparian species are inherently resilient under frequent and intense disturbance, but different growth forms or guilds respond differently to particular disturbance events. The rate of recovery in riparian communities depends on the intensity and frequency of disturbance events and the resilience of the community.

The high frequency of disturbance events in riparian zones means that there are many opportunities for the resilience of riparian plant communities to be compromised. Ecosystems that are naturally subject to moderate to extreme abiotic regimes, including riparian ecosystems, have a greater tendency to display alternative stable states that may be resilient to restoration management interventions.

Resilience and alien species The issue of structural/functional resilience and alien species can be considered from various perspectives. In some situations, alien species do not appreciably alter resilience. However, the arrival, establishment, persistence and proliferation of alien species can reduce resilience. Alien plant species can also enhance resilience. For example, consider the ecosystem function of primary productivity. Soil-nutrient levels and primary productivity have declined in some riparian ecosystems because of anthropogenic actions. For example, dam construction can trap fine sediments and flood-borne nutrients in reservoirs leading to below-dam changes, while intensive livestock grazing can result in erosion of upper soil horizons. Some of the alien (and native) species that have increased in riparian zones, such as *Prosopis* spp. and *Elaeagnus angustifolia* L., harbour nitrogen-fixing symbionts. This symbiosis may confer a competitive advantage to plant species in nutrient-depleted ecosystems. The establishment of these plants, and their role in increasing primary productivity and soil fertility, could be viewed as enhancing the resilience of ecosystems.

RESTORING RIPARIAN ZONES AFTER ALIEN INVASION: CONCEPTUAL CONSIDERATIONS

Restoration involves rebuilding an ecosystem with the aim of returning it to some previous condition. It usually entails re-establishing the species, communities, structure and ecological functions that prevailed in the system previously. Complete ecological restoration is generally impossible at the landscape scale because of land-use conflicts and costs. In riparian ecosystems it may be feasible to restore segments of the riparian corridor, but restoring the river's catchment area, which potentially has a large effect on the hydrological and fluvial processes, is usually not possible. Thus, the scale of and potential for restoration of the riparian zone is constrained by the condition of the catchment area. This makes it critical to have a detailed understanding of the temporal and spatial dynamics of the catchment landscape, including past natural and human-induced changes. The complex interactions between biotic factors and the physical environment in riparian zones impose thresholds that delineate options for intervention at a variety of spatial scales. Effective restoration therefore demands careful consideration of alternative states and positive feedbacks. The most realistic approaches for riparian restoration are either to work within limitations imposed by the catchment, focusing on reach-scale restorations, or to work in those catchments where goals are still achievable and/or where priority for conservation is high.

The conceptual model developed by Whisenant (1999) that invokes biotic and abiotic thresholds is useful in the context of riparian ecosystems that are both influenced by invasions and which are, by their nature, highly susceptible to invasion by alien plants. Where the inputs of physical energy, in the form of water or wind movement, are dominating forces in structuring an ecosystem, as in riparian zones, manipulating the abiotic components must be a pivotal consideration in ecosystem repair. The primary variables driving the distribution and abundance of biota in flood-prone

rivers are usually abiotic. For example, damming and diversions of rivers have caused the decline of many aquatic and riparian species and altered structure and function of many ecosystems. Restoring such areas requires the hydrologic regime (flood frequency and intensity) of the river to be restored first, since floods and sediment routing are critical for the creation of appropriate sites for colonisation by riparian species. Reinstating water and sediment flows can also directly affect the relative performance of native and alien species.

Biotic components such as vegetation structure and composition are the appropriate focus of repair targets in situations where hydrological and geomorphological functioning can support the intended assemblage of species, or where this has been (or can be) restored. Riparian zones that are patchily invaded, or have only recently become densely invaded by alien plants, can sometimes be restored to their historic, catchment-scale, species composition through biotic manipulations alone, by removal of the invasive species.

In practice, restoration needs to involve the setting of sequential, multi-step goals. In riparian situations, clear physical and biotic goals must be based on sufficient baseline data, but a major limitation is that reference systems for defining restoration goals are globally rare. In reality, aiming for a return to some historic condition is usually inappropriate, untenable and futile. Firstly, most riparian ecosystems have a long history of use by humans and have been extensively transformed over centuries, often making it impossible to know the historic species composition. Even if it was possible to eliminate the newcomers and prevent their recolonisation, it is often impossible or impractical to restore species known to have occurred there previously under present, likely highly altered, riverine conditions. Such endeavours will become increasingly futile as climate change alters many facets of riparian environments.

An alternative view to management/restoration of riparian ecosystems emerges if one accepts that riparian ecosystems are open and dynamic and that humans are an increasingly dominant part of most ecosystems. Under this view, management/ restoration should not aim to recreate some historic species assemblage, but to restore those processes that provide a given desired riparian ecosystem structure and function. If ecosystems are viewed as open and dynamic, re-creation of some historic condition becomes an exercise in nostalgia. If humans are viewed as part of the ecosystem, then plant species accidentally or intentionally introduced by humans become just another species in the ecosystem. The native/alien dichotomy can be counter-productive in restoration practices, leading to an over-emphasis on composition over structure and function.

There are many instances where a small number of highly influential alien plant species are clearly fundamental stressors and disruptors of ecosystem functioning. In such cases concerted efforts to remove these species, prevent or reduce the risk of them re-invading, and re-establish species that are more conducive to the desired functions, are appropriate and tenable. Such operations need to be conducted with due cognisance of the components of resilience and the determinants of abiotic and biotic thresholds. For example, where dense alien thickets have been present for a long time and/or have altered the fluvial-geomorphological processes of the river, a more natural erosion-sedimentation cycle may first have to be re-established following alien clearance before indigenous riparian vegetation may be restored. As long as the hydrological and geomorphological processes of the river catchment have not been impaired, for instance through widespread soil cultivation and erosion or increased abundance of alien plants, the historic rates and ranges of abiotic processes may return following alien plant clearance in the riparian zones. However, it is important to note that the commitment to clearing is a long-term one that requires acute attention to follow-up. Short-term projects lacking social or political will are unlikely to succeed. Further, complete removal of alien species may be more damaging in some situations than killing them standing (e.g. by ringbarking), or even leaving them untreated. Riverbank stabilisation measures may be required in situations where indigenous species have been eliminated and their recruitment is predicted to be slow. However, stabilisation should not be done where it is suspected that the alien thickets have caused increased sediment deposition and channel aggradation, as the first step of restoration should be to remove these sediments, and allow the river to return to a more natural geomorphology.

In summary, it is important to assess which abiotic and biotic thresholds have been crossed in invaded riparian zones, and to ascertain whether the removal of the invasive species alone is sufficient to stop further changes that are deemed undesirable and promote the recovery of natural vegetation in the riparian zone. Such assessments should be done within the context of the catchment area and the limitations imposed by any human-induced changes to fluvial and hydrological processes. It is prohibitively expensive to consider restoring, using plant re-introduction techniques, entire riparian corridors. It is almost always more appropriate to consider a set of minimum interventions for achieving various alternative restoration goals or trajectories.

Successful small-scale restorations of river reaches have been conducted. For example, the restoration of riparian forest via bare root and containerised plants. The planting or sowing of indigenous riparian species should accelerate recovery of riparian vegetation in highly altered riparian zones, for example following the clearance of dense and extensive thickets of alien plants, as indigenous propagule pressure is likely to be very low. In such situations, riparian vegetation refugia may be scarce and soil-stored seed banks depleted. Therefore, the recolonisation of riparian zones via suitable indigenous species dispersing into the area will be slow and the probability of re-establishment of the alien species, or incursion of other alien species, will be high. In highly altered rivers, the creation of nodes of indigenous riparian vegetation is likely to be an important method in promoting the long-term restoration of riparian zones.

Spontaneous or directed succession, which is a legitimate and convenient restoration tool in human-modified habitats, may be less efficient in riparian zones because of their dynamic nature and continuous propagule pressure from alien species. When considering spontaneous succession as a restoration tool, the settings of the specific project must be considered and scientific knowledge integrated into the restoration programme.

For many river reaches throughout the world, such as those in urban areas, natural riverine processes cannot be restored because the economic costs are too high or the social and political will are not present. In many cities, the floodplains of rivers have been converted to housing or industrial areas, restricting the riverbed to a small channel. Although the levees can be set back to some degree, the historic floodplains cannot realistically be reclaimed by the river. Large human settlements are sustained in arid regions by massive and extensive dam and reservoir systems and water distribution structures. Although the flow pattern of below-dam rivers can be naturalised to some degree, many dams are a permanent feature of the present culture. Rivers by their nature reflect their watershed and urbanised rivers are often vegetated by a mixture of the historically dominant species and a wide variety of introduced species, including landscape and agricultural plants and other cultivars. In such highly modified rivers, it is perhaps advisable to let plant communities 'self assemble' with species (alien or native) that are adapted to these novel conditions. Removal of alien plants from rivers in urban landscapes and other situations with pervasive human influence is, in almost every case, futile and potentially counter-productive with respect to maintaining ecosystem function. Efforts to remove the human footprint from the landscape also may be counterproductive with respect to human-nature interactions. There may be value, instead, in accepting and appreciating the fact that rivers reflect their watersheds, whether dominated by people or not. In such cases, the focus should be on maintaining river health and key ecosystem services, and managing the emergent communities that are best adapted to these novel conditions.

The concepts expressed in this paper have been used to define an objective decision-making framework for restoring riparian zones affected by invasive alien plants in South Africa (Holmes *et al*. 2005). They should also be useful for guiding such initiatives in other parts of the world, such as Australia.

ACKNOWLEDGMENTS

This paper is a preview of a report based on the work of an international team comprising D.M. Richardson, P.M. Holmes, K.J. Esler, S.M. Galatowitsch, J.C. Stromberg, S.P. Kirkman, P. Pyšek and R.J. Hobbs. All these people contributed substantially to the ideas expressed here. A more complete and fully referenced version of the paper is available from DMR. This work was funded by the DST-NRF Centre for Excellence for Invasion Biology.

REFERENCES

Holmes, P.M., Richardson, D.M., Esler, K.J., Witkowski, E.T.F. and Fourie, S. (2005). A decision-making framework for restoring riparian zones degraded by invasive alien plants in South Africa. *South African Journal of Science* 101, 553-64.

Whisenant, S.G. (1999). 'Repairing damaged wildlands: a process-orientated, landscape-scale approach'. (Cambridge University Press, Cambridge).