Restoration of Fragmented Landscapes for the Conservation of Birds: A General Framework and Specific Recommendations for Urbanizing Landscapes

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Abstract Humans fragment landscapes to the detriment of wildlife. We review why fragmentation is detrimental to wildlife (especially birds), review the effects of urbanization on birds inhabiting nearby native habitats, suggest how restoration ecologists can minimize these effects, and discuss future research needs. We emphasize the importance of individual fitness to determining community composition. This means that reproduction, survivorship, and dispersal (not simply community composition) must be maintained, restored, and monitored. We suggest that the severity of the effects of fragmentation are determined by (1) the natural disturbance regime, (2) the similarity of the anthropogenic matrix to the natural matrix, and (3) the persistence of the anthropogenic change. As a result, urbanization is likely to produce greater effects of fragmentation than either agriculture or timber harvest. Restoration ecologists, land managers, and urban planners can help maintain native birds in fragmented landscapes by a combination of short- and long-term actions designed to restore ecological function (not just shape and structure) to fragments, including: (1) maintaining native vegetation, deadwood, and other nesting structures in the fragment, (2) managing the landscape surrounding the fragment (matrix), not just the fragment, (3) making the matrix more like the native habitat fragments, (4) increasing the foliage height diversity within fragments, (5) designing buffers that reduce penetration of undesirable agents from the matrix, (6) recognizing that human activity is not compatible with interior conditions, (7) actively managing mammal populations in fragments, (8) discouraging open lawn on public and private property, (9) providing statutory recognition of the value of complexes of small wetlands, (10) integrating urban parks into the native habitat system, (11) anticipating urbanization and seeking creative ways to increase native habitat and manage it collectively, (12) reducing the growing effects of urbanization on once remote natural areas, (13) realizing that fragments may be best suited to conserve only a few species, (14) developing monitoring programs that measure fitness, and (15) developing a new educational paradigm.

Keywords: Birds · conservation · exotic species · fragmentation · landscape · natural disturbance · predation · urban ecosystems · restoration

Introduction

When humans occupy landscapes, we convert portions of the native vegetation to agriculture and urban development, and modify areas to varying degrees by harvesting natural resources (Villa et al. 1992). The ecological implications of our domination of the earth are complex (Vitousek

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et al. 1997), but the effects on land cover are rather straightforward: we *fragment* it. Once continuous mosaics of native vegetation become transformed into disjunct pieces of native vegetation surrounded by a matrix of cement, grass, crops, and degraded lands (Meyer & Turner 1992; Marzluff & Hamel 2001).

Fragmentation of natural landscapes is often detrimental to biodiversity because it involves the removal, reduction, and isolation of native vegetation (Fahrig 1999). As a result, remaining populations of native wildlife are smaller and perhaps exposed to new threats emanating from the human-dominated matrix. Relevant threats for bird populations include (1) competition with exotics such as *Sturnus vulgaris* (European starlings; Kerpez & Smith 1990), (2) exposure to larger populations of predators and parasites such as corvids, domestic cats, and *Molothrus ater* (brown-headed cowbirds; Robinson & Wilcove 1994; Marzluff & Restani 1999), (3) heightened disturbance and mortality from human activity (Johnston & Haines 1958; Knight & Gutzweiller 1995; Evans 1998), and (4) restricted and exposed dispersal corridors (Matthysen & Currie 1996).

The anthropogenic activities that fragment natural landscapes do not affect wildlife populations equally (Fig. 1). Globally, agriculture currently has the greatest effect on wildlife because 32% of the earth's land is planted in row crops or pastures (Houghton 1994). In many regions, agricultural practices are intensifying, which reduces similarity of land cover with native cover, introduces exotics, disrupts nutrient cycles, and adds pollutants (Newton 1998). Urbanization has the greatest local effect on wildlife because of its persistence on the landscape and its dissimilarity to natural land cover. The magnitude of the effect of urbanization (loosely defined here to include human settlement ranging from dispersed rural and exurban villages and homesteads to densely settled subdivisions and cities) depends on the amount of vegetation incorporated in settlements, especially native vegetation (Lancaster & Rees 1979; Beissinger & Osborne 1982; Mills et al. 1989). The pattern of development (clumped versus dispersed housing, for example) greatly affects the resulting fragmentation, but the effects of urban pattern on bird diversity are poorly known (Nilon et al. 1995). Timber harvest produces the least effect of fragmentation because harvested areas may regrow with native vegetation. However, when succession is slow, non-native vegetation is planted, natural structures are simplified, or harvest is done in landscapes not naturally fragmented, the effects of timber harvest can be substantial (Bierregaard & Lovejoy 1989). In general, the causal link between fragmentation and bird reproduction (increased nest predation and parasitism along newly formed edges) is greater when landscapes are fragmented by urban and agricultural development than when they are fragmented by forestry (Marzluff & Restani 1999).

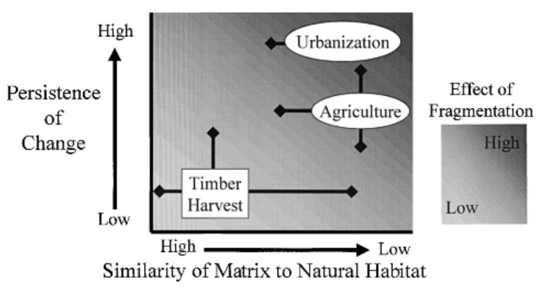

Fig. 1 Relative importance of anthropogenic agents of fragmentation. Urbanization, agriculture, and timber harvest all fragment native habitats, but urbanization is expected to have the greatest local effect on native animals because once an area is urbanized it rarely reverts to a more natural condition (high persistence of change) and the urban matrix is very dissimilar to native land covers. The effect of urbanization may vary depending on the mix of built, exotic, and native elements in the matrix (range of effect is indicated by line ending in diamond). Agriculture is expected to have intermediate effects on native animals that vary depending on the intensity of land conversion and use (range indicated by lines to diamonds). Timber harvest is expected to have the least effect on native animals, but this depends on the natural rate of success and tree growth which affect the persistence of the change, and the natural disturbance regime of the area which affects the similarity between harvested and natural land cover (range indicated by lines to diamonds)

Urbanization is likely to top agriculture as the dominant agent of fragmentation at the global scale. Currently only about 3% of the earth's surface is covered with buildings and other urban structures (Meyer & Turner 1992); however, the growing human population is becoming increasingly urbanized. By 2025 the global urban population is projected to equal today's world population (~6 billion, United Nations 1996). Therefore, the extent of urban development will increase. More importantly, the sprawl associated with many urban centers and the current tendency in developed countries to subdivide and settle formerly extensive ranches and wildlands (Berry 1990; Knight 1995; Buechner & Sauvajot 1996) means that increasingly large portions of the earth are fragmented by some form of human settlement. This is most evident when the pattern of lights produced by human settlement is viewed from afar at night (Marzluff & Hamel 2001). Because of the increasingly extensive, lasting, and large effects of fragmentation resulting from human settlement, and the typical emphasis in the literature on fragmentation resulting from other human activities (usually forestry; e.g., Harris 1984; DeGraaf & Miller 1996; Laurance & Bierregaard 1997; Rochelle et al. 1999), we restrict the remainder of our discussion to restoration of areas fragmented by urban development.

It is unreasonable to assume that habitat fragmentation will subside as long as humans dominate the earth. Therefore, restoration ecologists must determine how best to maintain wildlife diversity in fragmented landscapes. Nearly all suggestions in the conservation biology literature posit two solutions for preserving biodiversity in fragmented settings: (1) establish corridors among native patches or (2) buffer native patches with native habitat to increase their size and amount of interior area (Davis & Glick 1978; Soulé 1991; Shafer 1997). Both goals may be realized by first restoring fragments nearest reserves (Huxel & Hastings 1999), but we suggest that additional options exist and explore some of them that are relevant to birds in urban landscapes. Our objectives are to (1) offer a framework that links individual animal fitness to community composition so that we can better identify when and why fragmentation affects avian community composition; (2) highlight and review the large effects urbanization has on birds inhabiting remaining native habitats; (3) suggest how restoration ecologists, land managers, and urban planners can reduce the impacts of fragmentation in urbanized landscapes; and (4) suggest research that is needed to improve our ability to restore ecological function to urban fragments.

Maintaining Diverse Communities Requires an Understanding of Individual Fitness and Population Viability

Restoring wildlife diversity in fragmented environments will be more successful if restoration ecologists, land managers, and urban planners know how their actions affect the fitness (reproduction and survivorship) and dispersal of individual animals. Simply knowing that a management action increases or decreases the diversity of wildlife communities is insufficient (van Horne 1983). Understanding fitness and dispersal of individuals is important because these are the parameters that determine a local population's likelihood of growth or extinction and its dependency on (or importance to) other populations. Managers who know, for example, that corridors work in sage-scrub habitat because they allow coyotes to limit medium-sized mammals that prey on bird eggs and nestlings (Crooks & Soulé 1999) will be able to handle problems in a different landscape when corridors fail to enhance community diversity. They might see, for example, that a variety of predators use the corridors to the detriment of mammalian predators, as well as birds themselves. A change in corridor configuration or direct removal of some predators might restore bird community diversity. Managers unaware of why avian diversity is declining despite the presence of corridors might guess that the reserve needs to be larger or the corridor wider. These actions would likely be ineffective and possibly exacerbate the problem. In general, managers who know the causal links between their actions and population persistence can more effectively restore and maintain community diversity (Marzluff et al. 2000).

The focus on individuals and populations we espouse is often viewed as simplistic and today is thought to be relevant only for sensitive species requiring special attention (Knight 1990). In contrast, management of communities or ecosystems is perceived to be more balanced, economical, and effective. However, this is an inherently false dichotomy because the ability of local populations to persist in fragments (population viability) *determines* community composition and is *determined by* the ability of individuals of a species to reproduce and survive in fragments and to colonize fragments (Fig. 1). In other words, because communities are collections of species, they require detailed understanding of each species for effective management.

Community composition is unlikely to be a simple reflection of the individualistic responses of species to their environment (Fig. 2). Instead, a wildlife community is determined by the physiology, ecology, morphology and behavior of individual species (Gleason 1926), the constraints of various biological interactions (predation, competition, mutualism, parasitism), ecosystem function, past disturbance, and chance (Wiens 1989). However, the population dynamics of each species in the community is the fundamental determinant of community composition because a population's dynamics reflects the effects of all these factors on survivorship, reproduction, immigration, and emigration. This preeminence of population dynamics challenges the manager to monitor survival, reproduction, and dispersal, not just community diversity.

Appreciating and measuring population-level processes in highly fragmented landscapes often emphasizes the importance of dispersal to population persistence. Moreover, this often requires a regional, rather than local, perspective. For example, community diversity in fragments of midwestern forests may be high simply because of immigration from large forest blocks in the upper Midwest (Robinson et al. 1995). The diversity in fragments cannot be maintained unless large forests continue to be productive (i.e., fragments are sinks and distant forests are sources; Pulliam 1988). The manager of a fragment who monitors only local community diversity will blissfully think he is doing a great job until diversity inexplicably drops. The manager of a fragment who measures reproduction, survival, and dispersal will understand that dispersal is critical to his fragment's diversity and can be working to enhance reproduction and survivorship in the fragment, while also securing populations in distant, large blocks of forest.

Acknowledging the importance of individual fitness and population viability to community composition focuses our discussion of restoration in fragmented environments. To restore avian diversity in fragmented landscapes we need to determine if and how fragmentation affects reproduction,

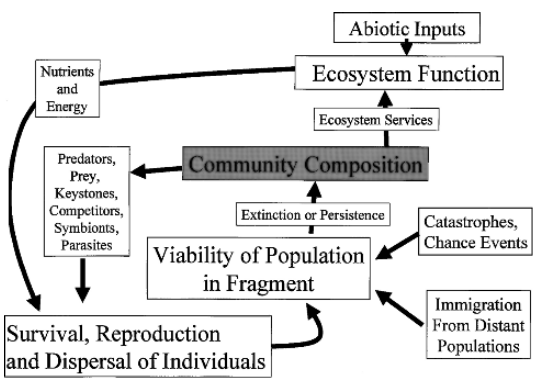

Fig. 2 How individual, population, community, and ecosystem properties interact to determine community composition. Survival, reproduction, and dispersal by individuals determine local population viability. This may be affected by immigration from distant populations and chance events. Population viability determines whether a population persists or goes extinct, and therefore defines community composition. Emergent properties of communities and ecosystems modify community composition through their effects on individual fitness. Thus, the restoration ecologist interested in maintaining diverse communities must restore, maintain, and monitor individual fitness and dispersal

survival, and dispersal of individuals in local populations. Likely pathways for these effects include (1) disruption of nutrient cycling and energy flow, (2) increases in predators, parasites, and competitors, and (3) reduction of immigration from distant populations (Fig. 2). The influence of fragmentation on each of these processes will be highly site-specific, but these are the processes that should determine individual fitness and population viability (Fig. 2). Individual fitness, dispersal, and population dynamics must be monitored to determine if restoration prescriptions are successful (i.e., correct the aberrant processes in a particular site and enhance survivorship, reproduction, and successful dispersal).

When Does Fragmentation Affect Bird Communities?

The effects of anthropogenic habitat fragmentation on fitness, population viability, and therefore community diversity and composition depend on two basic attributes of the landscape. First, the temporal frequency and spatial extent of the natural disturbance regime determines the natural patch dynamics (patch size, connectivity, and persistence) of an area. Patch dynamics are important agents of natural selection that determine the sensitivity of birds to unnatural fragmentation. Small volcanic flows, meandering rivers, localized windstorms, and low-intensity fires naturally fragment landscapes. As a result, birds have evolved good dispersal characteristics and utilize small patches and edges in such settings. Examples of these types of landscapes are active volcanic islands, intermountain forests of the western United States (Sallabanks et al. 1999), bottomland forests of the southeastern United States (Walters 1998), and natural wetland complexes. In these areas, bird (and other wildlife) diversity is reliant on fragmentation, not sensitive to it. Fragmentation provides a mix of small, short-lived habitat patches, each of which is used by distinct assemblages of birds. Removing the agent of fragmentation homogenizes the landscape and lowers bird diversity (Askins 1998). In contrast, large, homogeneous, interconnected patches of vegetation are produced by infrequent disturbances or extensive disturbances such as hurricanes, typhoons, and high-intensity fires that affect entire forest stands. As a result, natural selection favors birds that are sedentary and able to utilize resources provided in the patch. The poor dispersal abilities that have evolved predispose birds inhabiting such landscapes to being affected detrimentally by fragmentation (Soulé et al. 1988; Knick & Rotenberry 1995). Temperate and tropical rainforests, western United States shrublands and thornscrub, and tundra are examples of these landscapes.

The second factor determining the potential effects of anthropogenic fragmentation is the similarity of the land cover created by humans to natural land cover. When we surround remaining habitat fragments with natural vegetation (such as young forest during timber harvest operations) birds often show little response. For example, rates of nest predation (DeGraaf & Angelstam 1993; Marzluff & Restani 1999), nest parasitism (Tewksbury et al. 1998), and community diversity (Sallabanks et al. 1999) have been shown to be unaffected by forest fragmentation resulting from timber harvest. However, when we replace forests, grasslands, and wetlands with crops and urban settlement (land covers grossly different from natural ones) bird communities rapidly lose diversity (Wilcove 1985). The specific reasons for these losses and suggestions for minimizing them are discussed below.

How Does Urbanization Affect Birds in Remaining Fragments of Native Habitat?

Urbanization produces homogenous, dense, and often exotic communities of birds and mammals within settlements worldwide (Erz 1966; Bezzel 1985; Knight 1990; Marzluff et al. 1998; Blair 2001; Marzluff 2001). These communities and the human activity associated with urbanization affect birds that remain in relatively natural fragments by (1) increasing their natural predators and parasites; (2) attracting exotic predators, diseases, and competitors; (3) affecting trophic structures by removing top-level predators; (4) obstructing traditional migratory and dispersal routes and increasing the dangers of dispersal; (5) removing key resources like standing and downed deadwood, ground cover, and shrub patches; and (6) disrupting nutrient and hydrological cycles. We discuss each below with an emphasis on how they affect individual fitness and resulting community composition.

Increase of Native Predators and Parasites

Native species that are able to tolerate human activity benefit by the ameliorated climate, abundant food, and reduced predator populations in cities. Foremost among such species are corvids, small- to medium-sized mammals, brood parasites like brown-headed cowbirds, and a few raptors (Eden 1985; Fraissinet 1989; Marzluff et al. 1994; Bird et al. 1996; Konstantinov 1996; Danielson et al. 1997). These species forage to varying degrees in nearby fragments of native habitat and may even establish large populations in such habitats where they use native vegetation for nesting and exploit nearby urban food sources. The result of their increase is an increase in predation pressure on the eggs, nestlings, and occasionally adults of birds in fragments. These "subsidized predators" often are most abundant at the edge between urban lands and fragments, and therefore they often impact productivity of birds in fragments surrounded by urban development most severely at the fragment edge (Marzluff & Restani 1999). The result is that populations of native birds rarely reproduce well enough to be viable along the edges of fragments or in very small or linear fragments that have high ratios of edge to interior area (Wilcove 1985; Robinson et al. 1995).

Introduction of Exotic Predators, Diseases, and Competitors

Humans often purposefully or accidentally import exotic animals when they colonize new lands. This is a major cause of avian extinction (Diamond 1989) and a serious threat to any native birds in fragments near human settlements. *Felis domesticus* (house cats), *Rattus* spp. (rats), European starlings, and various diseases dramatically reduce reproductive success and survivorship of birds. On oceanic islands they are common agents of extinction. For example, after the ship *Makambe* ran aground on Lord Howe Island in 1918, rats escaped, colonized the island, and caused the extinction of five bird species (Hindwood 1940). In a similar way, introduced cats exterminated the *Cyanoramphus novaezelandiae erythrotis* (Macquire island parakeet; Taylor 1979), and malaria contributed to the extinction of at least four bird species on Hawaii (van Riper et al. 1986). On habitat islands the role of these agents is less well documented, but likely to be the same. Cats alone were estimated to kill 7.8–217 million birds per year in Wisconsin (Coleman & Temple 1996)! Cat populations are greatest in rural settings, but still substantial in urban areas (e.g., 1.5 million cats live in urban Illinois, compared to an estimated 4 million in rural Illinois; Warner 1985). As with native predators, exotic mammalian predators often inhabit forest-field and forest-development edges (Danielson et al. 1997; Mankin & Warner 1997). Avian communities may persist on habitat islands in spite of exotic predators, but the long-term prospect of persistence may be illusionary. Their persistence may be due only to immigration from less impacted "source" populations (Pulliam 1988; Robinson et al. 1997). Detailed study of reproduction, survival, and dispersal is the only way to determine this and identify effective management solutions.

Removal of Top-level Predators

While we supplement many predators, we remove many others, especially if they are viewed as a threat to our safety or that of our stock. Thus, at this time lions, tigers, bears, and wolves inhabit few urban areas. We remove other top predators in more indirect ways by interfering with their hunting or providing too little space for their needs. In this way, many large raptors, weasels, native cats, and canids are excluded. The result of predator removal is an increase in corvids, domestic dogs and cats, rats, and mice that then prey on native birds and their nest contents. The keystone role of predators was demonstrated in the coastal California scrub, where avian diversity dropped when *Canis latrans* (coyotes) were excluded from the landscape (Soulé et al. 1988; Crooks & Soulé 1999).

Installation of Dispersal Barriers

Dispersal is the aspect of avian population biology that we know the least about, but one we are certainly affecting with our building and development activities (Walters 1998). Roads, lights, buildings, and subdivisions do not provide the cover or food resources that birds need when they disperse from their natal habitat. Moreover, they include many obstacles capable of killing thousands of birds annually (Johnston & Haines 1958; Evans 1998). Tall (> 200 ft) towers alone are estimated to kill 2–4 million songbirds each year in North America (Evans 1998). Untold numbers are hit each year by automobiles. Interference with dispersal reduces community diversity because it lowers colonization of fragments and reduces the ability of healthy source populations to contribute breeders to distant habitat. Because of the long lifespans of many birds, the effects of reduced dispersal will often take decades to detect unless it is explicitly monitored.

Removal of Key Resources

Many humans abhor untidy landscapes. We remove and simplify ground cover, trim branches from lower reaches of trees, cut down dead trees, and fastidiously rake, haul, burn, or grind up fallen dead material. The result is a sterile landscape lacking nesting cover, cavity nest resources, and diverse insect, reptile, and amphibian communities that many birds depend on. This is an important reason that ground, shrub, and cavity-nesting birds are the first to disappear from human-dominated ecosystems (Emlen 1974; Gavareski 1976; Horn 1985; Tilghman 1987; Konstantinov 1996).

Disruption of Ecosystem Processes

Perhaps the greatest long-term effect of human domination on birds is our disruption of nutrient and water cycles, and diversion of primary productivity (Marzluff et al. 1998). Humans are estimated to use 25% of the earth’s primary productivity (Vitousek et al. 1986). Thus, less is available to other species. Our tendency to suppress fires and overuse water resources in proximity to dwellings changes bird habitat and reduces nutrient loads. Such degradation of the landscape extends far beyond the boundaries of cities (Wackernagel & Rees 1996), which may reduce reproduction and survivorship of birds in nearby native habitats.

Management of Native Fragments in Urbanized and Urbanizing Landscapes

Conserving biodiversity in urban landscapes requires two basic activities: (1) the design and establishment of a system of native vegetation reserves, and (2) the maintenance and restoration of ecological function in reserves. The first activity dominates the manager’s agenda in landscapes where sprawl is just beginning to encroach on large areas of native habitat. Much has been done to relate the theory of island biogeography to reserve design in such settings (Davis & Glick 1978; Knight 1990;

Soulé 1991; Shafer 1997). These authors uniformly recommend that (1) the area and numbers of reserves be maximized, (2) the amount of edge and degree of fragmentation within reserves be minimized, (3) the connectivity between reserves be maximized, (4) buffers be maintained around reserves, and (5) the scale of reserve planning be expanded beyond the local area to include entire watersheds and bioregions. However, the rapid pace of urbanization, the high cost of land acquisition, the diminishing availability of large parcels of native habitat, and increasing threats to existing reserves reduce the utility of reserve design guidelines to managers in urban settings. Rather than deciding on the optimal properties of fragments, managers are increasingly forced to decide whether to acquire new reserves or restore and manage existing ones (Schwartz & van Mantgem 1997).

In the fragmented landscapes that typify those settled by humans, managers must acquire as much native habitat as they can. Priority should be given to acquiring the largest parcels (Robinson et al. 1997) of native vegetation (Schwartz & van Mantgem 1997) in proximity to existing reserves occupied by sensitive species (Huxel & Hastings 1999). Small fragments of native habitat can conserve biodiversity (Schwartz & van Mantgem 1997), but mobile organisms like birds may require large, undisturbed reserves in some part of a bioregion to allow any fragments to be utilized (Robinson et al. 1995, 1997). Acquisition of native habitat may not be enough to conserve wildlife because reserves attract predators and parasites and are often heavily utilized for recreation by humans. As a result, birds may be attracted to reserves but may not be able to maintain viable populations in them (Robinson et al. 1997). Regional planning and active management and restoration of reserves is necessary. Given this premise, we provide a combination of short- and long-term restoration approaches and policy structures that we suggest will aid the conservation of wildlife diversity in general and avian diversity in specific in human-dominated ecosystems. No one approach is adequate. All the approaches considered together provide the planner, habitat manager, and restoration practitioner with tools for providing an environment that retains native species diversity.

Restoration of Ecological Function in Urban Landscapes

Little has been written about how to actively manage and restore fragments in urbanized settings. Here we offer 15 specific recommendations that would improve the suitability of reserves for birds. Above all, it must be assumed that the degree of fragmentation in the landscape will remain stable or increase. Therefore, the manager must be relentless in determining how individuals are performing (reproducing, surviving, and dispersing) in reserves and aggressive in restoring population viability within reserves. It may be prudent to prioritize the restoration and management of fragments nearest areas occupied by native species of concern (Huxel & Hastings 1999); however, we would caution managers first to make sure that populations in such areas are viable.

Managers have their greatest latitude to restore ecological processes within reserves, but much can also be done to manage the matrix surrounding the reserve. Therefore, we direct our suggestions to restoration within fragments and around fragments. Key elements that should be present in restored fragments include: standing deadwood, complex woody debris, complex vertical and horizontal structure, protected interior areas, undeveloped riparian zones, undeveloped slopes and cliffs, high native plant diversity, invasive plant control, minimal lawn area, high diversity of shrubs that produce berries, nuts, or nectar, control of exotic mammals including house pets, reduced supplementation of native predator and parasite populations, monitoring programs that measure fitness and dispersal, and integrated education, research, and outreach activities to foster citizen support. These are important regardless of fragment geometry and serve to underscore our general message that the ecological processes that produce viable populations, not just the habitat structure associated with viability, must be restored.

(1) Increase the foliage height diversity within fragments. MacArthur and MacArthur (1961) noted long ago that bird community diversity was positively related to foliage height diversity. Lancaster and Rees (1979) confirmed this association in native fragments imbedded in an urban landscape. This occurs because habitats with many vegetation layers (herb, shrub, sapling, canopy) provide more nesting, feeding, and hiding spots than habitats of uniform structure. Providing dense and variable ground and shrub cover is especially important in human-dominated ecosystems. These are the areas we tend to clean and simplify first, yet they are the areas that harbor native birds most likely to breed successfully in the face of strong nest predation (such sites are usually well hidden from avian nest predators). For example, urban woodlots in Massachusetts that had vertically and horizontally diverse vegetative structure contained richer avifaunas than simpler woodlots (Tilghman 1987).

Restoring or maintaining plant structural diversity may be an intermediate management goal. It keeps the manager's options open because a greater diversity of birds may find some portion of the reserve attractive. However, later the manager may want to emphasize and increase specific structural attributes needed by birds able to maintain viable populations in urban fragments (see [14] below). Structural diversity may also be a useful criterion for prioritizing parcels available for purchase.

(2) Maintain native vegetation and deadwood in the fragment. Structural diversity in vegetation may promote bird diversity, but simply maintaining the structure of the fragment is not adequate. Exotic vegetation must be actively controlled and native plants maintained and restored if native birds are to be retained in the fragment. Native vegetation has been found to be important to bird diversity in ecotypes ranging from deserts (Mills et al. 1989) to riparian zones (Rottenborn 1999) to deciduous forests (Beissinger & Osborne 1982).

When restoring small parcels, aim for diversity in plantings, in vertical structure, and in downed wood. Diverse wood on the ground provides high diversity of habitats for decomposers, invertebrates, and small mammals—all-important foods for birds (Wood 1989; Schuman & Belden 1991). Restoration must allow for continued recruitment of standing dead- and downed wood. This means that trees must be allowed to age, lose branches and upper portions, and become infected with organisms that decay their interiors (e.g., heart-rot fungi like *Phelinus pini* and *Fomitopsis cajanderi*). Nest boxes may be useful in the short term for secondary cavity nesters, but many cavity nesters also require natural foraging and nesting substrates provided only by dead-wood. A variety of active management techniques exists to speed the development of cavity resources and foraging sites needed by primary and secondary cavity nesters. These include topping large trees, killing trees, and injecting heart-rot fungi (Conner et al. 1981; McComb & Rumsey 1983; Bull & Partridge 1986; Baker et al. 1996).

(3) Manage the landscape surrounding the fragment (matrix), not just the fragment. In urban settings the primary reason that birds in native fragments fare poorly is that predators, parasites, competitors, chemicals, kids with BB guns, recreationists, and the like *from the matrix* intrude into the fragment. No amount of habitat restoration within the fragment will be adequate if the destructive forces in the surrounding landscape are not identified and reduced (Aronson et al. 1993). In most settings regulation, enforcement, education, and a variety of buffers and barriers (see [4] and [5], below) will be needed to accomplish this. A key issue to reduce in the matrix is food supplementation to exotic and native nest predators.

(4) Design buffers that reduce penetration of undesirable agents from the matrix. The standard approach to providing interior conditions is to design reserves to include "interior areas" (those more than 50–200 m from an edge: Soulé 1991; Shafer 1997; Rochelle et al. 1999). However, simple spatial buffers do not guarantee the safety of fragment interiors in urban areas because (1) native predators and parasites that live in fragment interiors are supplemented by resources in the matrix, and (2) many of the exotic predators, competitors, pollutants, and other agents we try to contain in the matrix are very mobile and able to penetrate buffers, especially if the composition of the buffer is suitable to them. Often, native habitat is suitable, if not optimal, to predators, parasites, and competitors (Marzluff et al. 2000). To prevent the problem of buffers acting as "wicks" that allow exotic and native predators and parasites to flow between the fragment and the matrix, we suggest buffers be as impermeable as possible. Often this means as unattractive to, and as devoid of, any wildlife as possible. Extremely dense, simple structured forest works well in this regard in the temperate rainforests of the Pacific Northwest (Marzluff et al. 2000). Heavily urbanized or intensively farmed areas would also insulate fragments from biotic invaders. If such buffers are proposed one should make sure that wildlife does not utilize these areas, and that polluted emissions and runoff, and noise are minimized.

(5) Recognize that human activity is not compatible with interior conditions. Interior (core) areas must be protected from humans as well as predators, parasites, competitors, and diseases. Fencing reserves, or making them difficult to enter in other ways, may help, but in multiple-use reserves, recreational use of interiors and buffers must also be limited. Buffers that include trails, for example, may foster the travel of disruptive agents from the matrix into the fragment. Even innocuous activities like nature watching need to be excluded from core areas because they can disrupt breeding birds (Knight & Gutzweiller 1995).

(6) Make the matrix more like the native habitat fragments. In the application of island biogeography theory to reserve design, the size and closeness of islands become less and less important determinants of animal diversity as the matrix becomes more similar to the habitat islands. The reason for this is that the matrix interferes with normal movements between fragments in proportion to its dissimilarity with the habitat preferences of animals. Increasing the similarity between the fragments and the matrix can be accomplished by leaving or creating many small areas of native habitat in the matrix, with plant and structural complexity and protected in some way from intrusion (Berger 1993). In the city these habitat areas can be created at street ends, along streams, in parks, on slopes, between rail and street corridors, on municipal property such as at treatment plants, along shores, around wetlands, on airports, or on islands. Private landowners with large lots can contribute to this effort by planting small portions of their land with native vegetation. Urban planners and managers could create stepping stones between reserves by promoting naturalization of the matrix in strategic locations. This may help retain biodiversity in reserves (Shafer 1997), provided that such remnants do not act as sinks. Special attention should be paid to naturalizing and protecting naturally linear areas like riparian zones that may be normal dispersal corridors (Mankin & Warner 1997).

(7) Actively manage mammal populations in fragments. When humans remove medium- to large-sized predators from ecosystems, small and medium-sized mammal populations often increase (Soulé et al. 1988). In urban areas many of these mammals are exotics that are efficient bird predators (Crooks and Soulé 1999). The house cat is the single most important mammal in this respect. A single cat can wipe out populations of entire species within fragments. An important component of habitat restoration includes restoration of a balanced small- to medium-sized native mammal community. This will require trapping and removing all exotic mammals, educating and regulating surrounding landowners to keep their cats indoors, and intensive monitoring of mammal activity within fragments.

Avian nest predators and parasites (e.g., corvids, brown-headed cowbirds) may need to be controlled in special instances (e.g., to protect endangered species like *Dendroica kirtlandii* [Kirtland's warblers] Marshall et al. 1998), but we suggest that reducing food supplementation in the matrix and designing effective buffers are more permanent solutions to these problems.

(8) Discourage open lawns on public and private property. The typical American lawn is an ecological disaster that reduces biodiversity, contributes to global warming, stresses water supplies, uses global fossil fuels, and encourages the use of pesticides and herbicides (Bormann et al. 1993). The organic soil, litter, woody debris, herbaceous layer, shrub layer, and tree saplings excluded from lawns provide a complex habitat substrate for microbes, invertebrates, small mammals, and birds. Urban planners and managers should discourage open lawns on public property and reward lawn minimization on private property. Encourage landowners to reduce lawn and diversify their ground and shrub cover by providing information on the importance of these resources, creating backyard wildlife refuge programs, and providing property tax incentives. Residents of King County, Washington, for example, receive substantial tax breaks (50–90% reductions in property taxes) for maintaining natural undisturbed areas on their properties (King County Public Benefit Rating System).

(9) Provide statutory recognition of the value of complexes of small wetlands. Complexes of small wetlands may be especially important in urban settings (Adams 1994). Because they are considered to be of little consequence individually, the small wetlands may be subjected to piecemeal loss from land development or its consequences. Smaller wetlands tend to fall by the wayside because they may not be inventoried by any regulating agency; they may be unreported or below the threshold size for regulation (10–20 ha). In addition, landowners may simply not recognize them as wetlands when development or site modifications are contemplated. However, small complexes have many positive values such as extensive aquatic-terrestrial interfaces, maximization of productive shallow, saturated areas, complicated canopy and edge structure, aggregate water storage capability, and seclusion. They may promote dense nesting colonies of birds (Weller 1994), and, when clustered, they provide nearby destinations when waterfowl are flushed. They add to landscape diversity (Adams 1994).

(10) Integrate urban parks into the native habitat reserve system. Parks have multiple users, but it must be recognized that multiple uses cannot be carried out on every square foot of a park without severely degrading the habitat quality for wildlife. We suggest that parks with good habitat or adjacent to good habitat should have an emphasis on wildlife values, and sites with poor habitat potential should be used for more intensive human recreational sites (e.g., ball fields, picnic areas). Trails can be built through or adjacent to wildlife areas, but the integrity of such areas should be kept in mind when park design is accomplished (see [5] above).

(11) Anticipate urbanization and seek creative ways to increase native habitat and manage it collectively. Increasing reserve systems in urban landscapes will be difficult but necessary to maintain biodiversity. Two promising ways to accomplish this task are: (1) creation of public-private partnerships to reserve substantial amounts of native land cover (e.g., in Wisconsin and Illinois; Herkert 1997; Stearns & Matthiae 1997), and (2) establishment of "mitigation banks" where developers mitigate habitat losses by contributing to a fund for purchasing available open space (Soulé 1991).

Incentives for participants and coordinated management of individual parcels at local, regional, and national levels are necessary to reduce redundancy and conserve the greatest possible share of species. An example from an urbanizing landscape of utilizing the inevitable fragmentation in a land use system driven by economics is the Lower Rio Grande Valley National Wildlife Refuge (NWR) in south Texas (Jahrsdoerfer & Leslie 1988). Two self-contained refuges exist in the area around the mouth of the Rio Grande: The Santa Ana and Laguna Atascosa NWRs. The Lower Rio Grande Valley NWR was formed primarily to manage fragmented parcels, and currently contains almost 100,000 acres, stretching from the last dam on the Rio Grande to its mouth (about 150 miles). Parcels with intact thornscrub are purchased when possible, but parcels are also purchased from farmers who can no longer profitably farm them (because of salt or lack of water). Farmers are paid to continue to farm while converting 10 to 20% a year back to thornscrub. The farmers are paid to prepare and plant the restoration sites. The vegetation is quick growing and the corridor of parcels provides a matrix of satisfactory habitat dispersed among the farmland. Bird watching has become a major economic industry in south Texas, with the legislature allocating funds this year for a primary birding center with three satellite centers.

This example points out the importance of restoring native habitats and preserving them before extensive urban development (and the associated increase in property value) occurs. Since inception of the habitat buy-back plan, the lower Rio Grande has become the third-fastest growing area in Texas, and two urban centers (McAllen and Brownsville) now contain over 845,000 people (Texas State Data Center, Texas A&M University). Urbanization is certain to increase because seven new international bridges are proposed along the area's 50-mile section of the Rio Grande. As property values increase, farmers are likely to benefit more from subdividing for development than from restoring thornscrub (Wuerthner 1994). Successful expansion of the reserve area will become increasingly difficult as urbanization proceeds. Conservationists should anticipate urbanization in currently rural areas and create public-private partnerships to reserve and restore native land cover while property value is low. Using incentives for participants and coordinating reserve management in urban landscapes, where development is always profitable, will be more difficult but creative managers and planners can find opportunities to purchase strategic properties and encourage nearby landowners to restore a portion of their land.

(12) Reduce the growing effects of urbanization on once remote natural areas. Large areas of native habitat on the fringes of development are likely to be important sources of colonists for fragmented habitat. Their preservation is crucial. The manager interested in maintaining avian diversity in a small local fragment has much to gain by maintaining large, distant sources (Robinson et al. 1997). Growth management policies, economic incentives to reduce subdivision, mitigation banking to purchase distant open space, and incentives that allow farmers, ranchers, and foresters to resist selloff and conversion to urban developers are important tools to minimize the global effects of urbanization (see [11]).

(13) Realize that fragments may be best suited to conserve only a few species. As the matrix becomes more hostile to native birds, those in fragments will likely have difficulty reproducing and surviving well enough to maintain viable populations (Murphy 1988). A few species may be relatively successful, and we encourage the manager to identify those and restore habitat to make sure they continue to succeed. Generalists, concealed nesters (often grassland and shrub nesters), aerial foragers, and flocking species may be especially suitable for such management. Robinson et al. (1997) suggested that Illinois managers in chronically fragmented landscapes focus on preserves of grassland and shrubland rather than forest because viable populations of forest birds were unlikely to be maintained in fragments near agriculture. Such difficult decisions will be necessary and should be part of a regional management planning effort so that birds not protected in fragments are protected elsewhere in large reserves (Robinson et al. 1997).

(14) Develop monitoring programs that measure fitness. Restoration must include a monitoring component for determining if our well-intentioned activities actually work. As we argued earlier, simply measuring the diversity of birds using restored areas is not adequate. Managers must monitor the reproduction, survival, and dispersal of individuals to accurately gauge their progress. This information is difficult and expensive to obtain, but is essential. Mist netting and color banding can provide information on survival and movements (DeSante & Rosenberg 1997), but information on reproduction is also needed. An approach that combines monitoring of diversity, reproduction, survival, dispersal, and predator populations is feasible and is described by Donnelly and Marzluff (in press). Monitoring programs are ideal ways to encourage landowner and local conservation group participation.

(15) Develop a new educational paradigm. The public needs to understand how humans affect wildlife and what they can do to minimize their effects. Traditional extension, outreach, summer nature camps, and school programs are helpful, but they are only a start. To further engage the public in wildlife conservation, we suggest that high-profile, collaborative efforts among [or involving] reserve managers, urban planners, K–12 schools, local management agencies and municipalities, universities, and conservation organizations are needed. For example, in Phoenix and Seattle new programs (funded in part by the National Science Foundation) are encouraging researchers to work with managers to design experiments and monitoring programs that address urban ecological questions. Graduate, undergraduate, and K–12 students, local residents, and conservation groups are used to collect and analyze data. The greater public participation fostered by these programs and the stronger link between research and management should increase public support, applicability, and utility of the knowledge gained.

Research Needed to Improve Fragment Restoration

The restoration of functioning ecosystems in severely degraded areas is one of the greatest challenges facing conservation biologists. Although we suggest many ways for restoration ecologists and land managers to increase the ecological functioning of native habitat fragments in urbanized landscapes, research will be needed to guide the way. The following areas of uncertainty would benefit immediately from creative investigations.

(1) Are corridors used by dispersing birds and do they facilitate the functioning of metapopulations? Debate exists about the functioning of corridors as travel ways. We would benefit by knowing how to make corridors that funnel rather than trap moving birds. The use of corridors by nest predators also needs more study to determine if the benefits to dispersal outweigh the detriments of increased nest predation. The central question really is: are bird populations in fragments maintained by dispersal from distant sources and, if so, how do we facilitate this "rescue effect" without simultaneously dooming the survivors with increased disease transmission, higher predator loads, and greater risk of catastrophe?

(2) Does increasing native vegetation of the matrix help? We have called for managers to recognize the importance of the matrix to the fragment and increase its natural components. But how much is needed to increase the functioning of fragments? What types of natural components minimize the effects of fragmentation most of all? Are small patches of native shrubs or scattered standing dead trees useful?

(3) How does the pattern of housing affect avian population viability in surrounding fragments? Although we cannot reduce the amount of urban space, we can control how densely it is settled. To lobby for development most compatible with avian conservation, we need to know whether clustered and dispersed housing developments affect birds differently. One study from the deciduous forests of Missouri suggests that dispersed housing developments have less effect on native bird communities than clustered developments (Nilon et al. 1995). The generality of this result needs confirmation.

(4) How do we design effective buffers that shield birds in fragments from the disturbance of the matrix? Distance will likely not be a sufficient buffer, but how do we make buffers that inhibit predators, competitors, and humans that also do not unduly constrain the species we are trying to conserve inside fragments? The search for the ultimate "semipermeable membrane" to buffer fragments should be conducted in the form of replicated experiments that test various combinations of land covers separating fragments from the extensive matrix.

(5) How does urbanization affect insect communities? Insects are critical food resources for birds, especially during the breeding season, yet little is known about their composition and abundance in urban areas. Even less is known about how they relate to bird populations. Urban insect communities are rich and include many exotics (Lutz 1921). Richness may be related to abundant ornamental plantings in urban areas (M. Deyrup, Archbold Biological Station, personal communication, 1999). Community composition of urban and wildland insect communities differs in subtle ways. For example, streetlights favor some moths over others, and loss of large rotting wood reduces rotten-log insect communities (M. Deyrup, Archbold Biological Station, personal communication, 1999). Loss of rotten-log communities may affect some woodpeckers, such as *Dryocopus pileatus* (pileated woodpeckers), because carpenter ant numbers would decline. Connections between such changes in community composition and bird population viability are basically unknown. Urban insects usually are met with insecticides, and the secondary effects of these on birds are mostly anecdotal.

(6) Is it possible to use some non-native plant species to reduce invasions by species known to be disruptive to ecosystem function? For example, *Rosa nutkana*, the native rose, is prone to blackberry invasion, but the non-native *R. rugosa* is not. Could *R. rugosa* be used to create a synthetic landscape that would not allow invasives to penetrate? Would the non-native plant naturalize and become a problem? Would it function as a food source in the landscape like its native congener? Do the benefits of limiting invasives outweigh the potential costs of increasing non-native plant abundance?

(7) Can fragments of native habitat in urbanized landscapes make tenable contributions to avian conservation? If urban fragments require continuous input of colonists from distant sources, are they really helping conserve birds or are they functioning as ecological traps? A modeling approach that would determine the contribution of urban fragments to regional bird population viability could suggest important aspects of populations in urban fragments that should be quantified.

(8) What are effective means of encouraging citizens to conserve birds and their habitats and reduce their impacts? Many Americans want a variety of birds in their yards and parks but never think twice about letting their cats roam or expanding their prized lawns. How do we inform their decisions with current science? Collaborations between ecologists, policy scientists, and urban planners will be fruitful in this arena (Alberti et al. unpublished.).

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