CONSERVATION THRESHOLDS FOR LAND USE PLANNERS

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Encroachment, Gnatcatcher Habitat
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Conservation Thresholds for Land Use Planners

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INTRODUCTION

While there are many threats to biological diversity in the United States, the loss and fragmentation of habitats and ecosystems have become the most significant (Wilcove et al. 1998). The survival of plant and animal species and whether our natural systems will continue to provide essential services—recycling of nutrients, flood and pest control, and maintenance of clean air, water, and soil—significantly depends upon where and how land is used, converted, and managed. Land use change resulting from development and associated human activities (e.g., agriculture, grazing, forest harvesting, and hunting) often alters the abundances and varieties of native species; introduces novel and potentially detrimental species to an area; and disrupts natural water and nutrient cycles, and natural disturbance patterns (e.g., fire) (U.S. Geological Survey 1998).

> *"Spatial planning is most significant in nature conservation when 10-40% of the natural vegetation has been removed from a landscape."*
>
> Forman and Collinge (1997), Landscape and Urban Planning 37, p. 129

Everyday, land use planners are faced with decisions regarding whether and how land is developed, parcelized, and used, and in what pattern. For the most part, such land use decisionmaking occurs without taking into account individual and cumulative impacts to biological resources. Implementing biologically sensitive spatial planning early in the development process will help preserve our natural heritage for the future, since the most crucial time for planning is when the first 10 to 40 percent of the natural vegetation is altered or removed from the landscape (Forman and Collinge 1997). A growing interest exists among land use planners and developers to use the tools at their disposal to better protect biological diversity. However, these professionals often lack the necessary information to incorporate ecological principles into their decisionmaking and to transform their traditional planning approaches into progressive, ecologically-based conservation tools.

To encourage and facilitate better integration of ecological knowledge into land use and land management decisionmaking, the scientific community needs to provide planners with applicable ecological information and guidance. To this end, the Ecological Society of America (ESA) convened a committee of leading scientists to identify principles of ecological science relevant to land use and to develop guidelines for land use decisionmaking.[1] The result was the development of eight general guidelines to assist land use planners in evaluating the ecological consequences of their decisions (*see* Box 1).

Conservation guidelines, such as those established by the ESA Land Use Committee, are designed to be flexible and to apply to diverse land use situations. As a result, they tend to be general in nature. For ecological principles to be put into practice, however, land use planners will need more specific information on potential threshold responses of species and ecosystems to development activities, particularly in relation to habitat fragmentation. To facilitate the adequate preservation of contiguous or connected natural areas, land use planners will need to know what science tells them about the minimum sizes of habitat patches species need to survive, or the amount of habitat necessary for the long-term persistence of native populations and communities in a region. In addition, they need information about the adequate size and placement of habitat corridors that would facilitate species movement and colonization among disjunct habitat patches, and about recommended widths of riparian buffers to protect water quality and provide wildlife habitat. Similarly, knowing the extent to which edges influence natural habitats would help land use professionals evaluate the effective area of any given habitat patch or corridor. Other fragmentation thresholds—such as the maximum distance between isolated patches tolerable in a landscape before ecological processes and patterns become disrupted—would arm decisionmakers with specific parameters that could be incorporated into land use design and modeling.

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[1] "The Ecological Society of America (ESA) is a non-partisan, nonprofit organization of scientists founded in 1915 to: promote ecological science by improving communication among ecologists; raise the public's level of awareness of the importance of ecological science; increase the resources available for the conduct of ecological science; and ensure the appropriate use of ecological science in environmental decision making by enhancing communication between the ecological community and policy-makers."
As cited in Ecological Society of America. "About ESA." <www.esa.org> (31 July 2002).

Given the inherent complexity of ecological systems, scientists are understandably reticent about providing exact prescriptions for land use planning and design because answers vary depending on the species, ecosystem, or scale in question. Nevertheless, by not promoting the use of even partial knowledge about species or ecosystem responses to human disturbance and fragmentation, the result is that land use decisions—even the most well-intentioned—are being made completely uninformed by science.

BOX 1. GUIDELINES FOR LAND USE PLANNING AND MANAGEMENT

In the face of rapid land use change, the Ecological Society of America's Land Use Committee recommends that land use planners and developers take into consideration the following eight guidelines to evaluate the potential impact of their decisions on our natural systems (*see* Dale et al. 2000 for full discussion):

1. Examine the impacts of local decisions in a regional context.

The persistence of species and the sustainability of ecosystems are determined not only by immediate surroundings but also by larger landscape factors, such as how habitats are interspersed across the landscape. Thus, local land alterations may have broad-scale regional impacts. Land use planners should both identify the surrounding region that is likely to affect and be affected by a local project and examine how adjoining jurisdictions are using and managing their lands. Regional environmental data (e.g., land cover classes, hydrologic patterns, and habitats for species of concern) should be incorporated into the decision-making process to facilitate a regional assessment of impacts.

2. Plan for long-term change and unexpected events.

Ecological processes, such as nutrient cycling, energy flow patterns, and disturbance regimes, may function over lengthy and variable time scales. In addition, ecosystems change over time. As a result, impacts posed by land use decisions are often long-term and unpredictable. Impacts may be delayed and not fully realized until years or decades later, or they may be cumulative such that a "unique trajectory of events" results that could not have been predicted from any single event. The complexity and variability of ecosystem responses dictate that land use decisions consider potential occurrences and implications of unanticipated and long-term events (e.g., variations in weather and disturbance patterns).

3. Preserve rare landscape elements and associated species.

Rare landscape elements, such as wetlands, riparian and mountain zones, and old-growth forests, often provide critical habitats for rare and endangered species. To protect a region's biological diversity, the natural diversity within a landscape must be preserved. Land use planners should identify the location of rare and unique landscape elements, by methods such as inventory and analysis of vegetation types, geology, hydrology, and physical features, and by their associated species. Once such landscape elements are identified, development should be guided away from such areas and toward more common landscape features.

4. Avoid land uses that deplete natural resources over a broad area.

Depletion of natural resources over time will lead to the irreversible disruption of ecosystems and associated processes. Consequently, land use planning and development should strive to prevent the diminishment of natural resources (e.g., soil, water, and habitat types such as wetlands) in any given area by identifying vital or at-risk resources and by taking the necessary precautions to avoid actions that threaten resource sustainability. Certain land uses or land activities may be deemed altogether incompatible in particular settings.

5. Retain large contiguous or connected areas that contain critical habitats.

Large habitat patches typically support a greater diversity and abundance of plants and animals and can maintain more ecosystem processes than small patches. Large intact habitats provide more resources, allowing larger populations of a species to persist, thus, increasing the chance of survival over time. Parcelization of large habitats often decreases the connectivity of systems, negatively affecting the movement of species necessary for fulfilling nutritional or reproductive requirements. To counter such effects, large intact areas and small areas that are well connected to other critical habitats should be protected.

6. Minimize the introduction and spread of non-native species.

Non-native species often negatively affect the survival of native species and disrupt the functioning of ecosystems. The spread of non-natives is facilitated by the development of transportation infrastructure and by the creation of edge environments and artificial landscapes. Land use professionals should strive to minimize the potential introduction and spread of non-native species into natural environments.

7. Avoid or compensate for effects of development on ecological processes.

Development may not only cause site-specific impacts, but may also disturb regional ecological processes. Ecological processes, such as fire, grazing, dispersal patterns, and hydrologic cycles, help to sustain plant and animal populations across a landscape. Thus, land uses that could negatively affect other systems or lands through the disruption of these processes should be avoided while those that benefit or enhance ecological attributes should be encouraged.

8. Implement land use and land management practices that are compatible with the natural potential of the area.

The natural potential of a site, as determined in part by local physical and biologic conditions, should be factored into how land is used and managed. Land uses that do not take advantage of a site's natural potential or consider its limitations, will likely result in unnecessary resource loss and high economic costs.

For more information on ecological principles to guide land use planning decisionmaking, see Dale et al. (2000), Duerksen et al. (1997), and Dramstad et al. (1996).

FROM GUIDELINES TO THRESHOLDS

The Environmental Law Institute (ELI) surveyed existing scientific literature to determine whether a body of knowledge has emerged within the scientific community relevant and applicable to national land use decision-making, specifically pertaining to biological conservation thresholds. A literature search of the major ecological, conservation, and land use journals was conducted using the Science Citation Index (ISI Web of Science) using search terms under the following categories: habitat fragmentation,[2] buffers,[3] corridors,[4] ecological thresholds,[5] and indicator species.[6] To increase applicability to current land use decisionmaking in the states, the search was confined to studies pertaining to the continental United States, as well as articles published between 1990-2001, and pre-1990 articles commonly cited within the scientific community. Only those articles containing quantitative information directly relevant to determining conservation thresholds for land use planning and land management were considered.[7] In addition to the literature search, review papers found in the gray literature (e.g., those produced by land management and regulatory agencies) were also included when possible and applicable.

ELI found adequate information on potential ecological threshold measures for the following areas: habitat patch area, percent of suitable habitat, edge effects, and buffers. Corridor design is reviewed in brief; however, specific guidance on corridor size was not feasible given inadequate available information within the scientific literature. This survey reflects scientific information largely related to habitat fragmentation and landscape ecology issues, with a focus on the spatial relationships (e.g., size, shape, location) and interactions of land attributes over large geographic areas.[8] This review does not cover other important conservation elements such as how to account for the biological integrity or ecological significance of habitat patches, which land use planners should consider when determining which parcels of land to protect. In addition, the thresholds presented in this review does not adequately address the conservation of species or habitat types that are naturally rare or localized (e.g., those with patchy distributions or limited ranges).

This report summarizes the Institute's findings and provides a platform for identifying gaps in existing knowledge to help guide more in-depth ecological research directly applicable to land use planning. This report in no way attempts to misrepresent the complexity of species and ecosystem response to land conversion, degradation, and fragmentation by providing simplified prescriptions. Land use planners should cautiously interpret the presented threshold values and ranges and tailor them to their unique circumstances and geographic settings.

First and foremost, land use planners need to establish their priorities for conservation—whether they be water quality or quantity, wildlife habitat, or biodiversity. In addition, conservation targets need to be established—whether they be regionally rare or endangered species or unique landscape elements (e.g., wetlands, old growth forests, riparian zones), or other targets—because this will directly influence the value and scale of any threshold.[9] Thresholds should be chosen or developed to meet the needs of the resources a locality is most concerned with managing and conserving. Planners should place great emphasis on evaluating site-specific and regional physical and biological conditions that influence the resiliency of particular systems to human disturbance.

The threshold values presented in this report should not detract from the larger goals of conserving or restoring indigenous species, rare and representative habitats, ecosystem functions, and natural connectivity. Where possible, the ESA land use guidelines should be followed. Land use planners should strive to protect large, intact parcels of land, high quality and ecologically important habitat, and where appropriate, should connect protected natural areas. When development is deemed necessary, land use planners should promote more compatible land uses and avoid or minimize fragmenting habitat patches wherever possible.

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[2] To locate papers with potential habitat fragmentation threshold information, the following search terms were used: minimum habitat size, habitat size, habitat requirement, habitat fragmentation, patch size, minimum fragment size, island biogeography, landscape connectivity, habitat connectivity, and metapopulation theory.

[3] To locate papers with potential threshold information on buffer width, the following search terms were used: riparian buffer, wetland buffer, buffer zone, buffer distance, forest buffer, buffer width, and buffer size.

[4] To locate papers with potential threshold information on corridor width, the following search terms were used: fragment connectivity, boundary permeability, landbridge, highway overpass, highway underpass, stream cross, habitat corridor, corridor, migration corridor, riparian corridor, and underpass.

[5] To locate papers with potential ecological threshold information, the following search terms were used: ecological threshold, conservation threshold, environmental threshold, and landscape threshold.

[6] To locate papers with potential threshold information relevant to indicator species, the following search terms were used: indicator species, indicator species and habitat fragmentation, and indicator species and thresholds.

[7] The majority of the papers encountered and selected focus on terrestrial species and to a lesser extent freshwater aquatic communities.

[8] As defined by Risser et al. (1984), "Landscape ecology considers the development and dynamics of spatial heterogeneity, spatial and temporal interactions and exchanges across heterogeneous landscapes, influences of spatial heterogeneity on biotic and abiotic processes, and management of spatial heterogeneity."

[9] Thresholds presented in this report reflect a taxonomic bias in the scientific literature toward birds and mammals. Thus, for many of the recommended threshold values, these two animal groups are assumed to be the conservation targets.

BOX 2. DEFINITION OF TERMS

Biological diversity (or biodiversity) – the variety of life and its processes, which includes the abundances of living organisms, their genetic diversity, and the communities and ecosystems in which they occur (The Keystone Center 1991). Diversity at all levels from genes to ecosystems need to be maintained to preserve species diversity and essential ecosystem services like climate regulation, nutrient cycling, water production, and flood/storm protection (Dale et al. 2000).

Biological (or ecological) integrity – refers to a system's wholeness, including presence of all appropriate elements and occurrence of all processes at appropriate rates, that is able to maintain itself through time (Angermeier and Karr 1994).

Boundary – a zone comprised of the edges of adjacent ecosystems or land types (Forman 1995).

Corridor – a linear strip of a habitat that differs from the adjacent land on both sides, connecting otherwise isolated larger remnant habitat patches (Forman 1995, Fischer et al. 2000).

Buffers – linear bands of permanent vegetation, preferably consisting of native and locally adapted species, located between aquatic resources and adjacent areas subject to human alteration (Castelle et al. 1994, Fischer and Fischenich 2000).

Ecosystem – a geographic area including all the living organisms (e.g., people, plants, animals, and microorganisms), their physical surroundings (e.g., soil, water, and air), and the natural cycles (nutrient and hydrologic cycles) that sustain them. Ecosystems can be small (e.g., single forest stand) or large (e.g., an entire watershed including hundreds of forest stands across many different ownerships) (USFWS 1994).

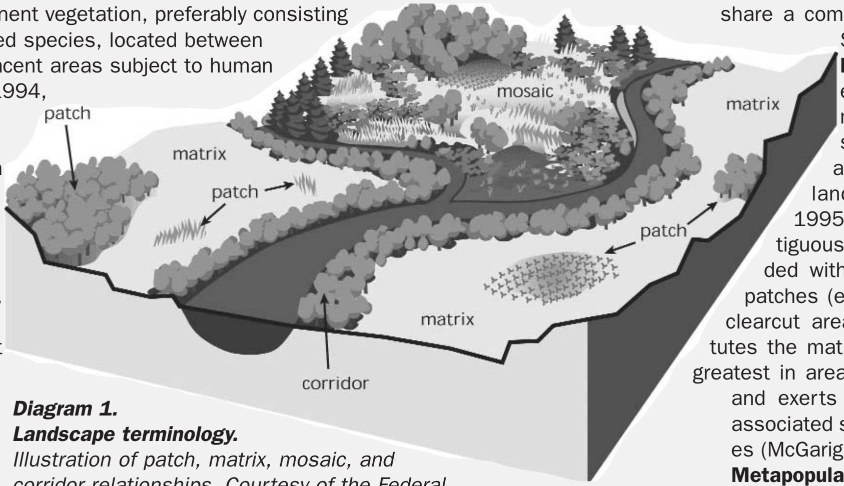

Diagram 1.
Landscape terminology.
Illustration of patch, matrix, mosaic, and corridor relationships. Courtesy of the Federal Interagency Stream Restoration Working Group (FISRWG), Stream Corridor Restoration: Principles, Processes, and Practices (10/98).

Ecosystem functions – the biophysical processes that take place within an ecosystem, apart from any human context (e.g. nutrient, energy, and hydrologic cycling; or soil formation).

Ecosystem services – refer to the ecosystem goods (e.g., food, and medicine) and services (e.g., climate regulation, water purification, and flood control) that humans derive benefit, directly or indirectly, from ecosystem functions (Costanza et al. 1997).

Ecosystem sustainability – the tendency of a system to be maintained or preserved over time without loss of decline to elements such as its structure, function, diversity, and production. Sustainability is widely regarded as economically and ecologically desirable and the only viable long-term pattern of human land use (Dale et al. 2000).

Edge – the portion of an ecosystem or habitat near its perimeter, where influences of the surroundings prevent development of interior/core-area environmental conditions (Forman 1995).

Edge effects – the negative influence (e.g., such as the profound modifications of biological and physical conditions) of habitat or ecosystem edges on interior conditions of habitat or on associated species (Meffe and Carroll 1997, Lindenmayer and Franklin 2002).

Habitat – consists of the physical features (e.g., topography, geology, stream flow) and biological characteristics (e.g., vegetation cover and other species) needed to provide food, shelter, and reproductive needs of animal or plant species (Duerksen et al. 1997).

Habitat fragmentation – the breaking up of previously continuous habitat (or ecosystem) into spatially separated and smaller parcels. Habitat fragmentation results from human land use associated with forestry, agriculture, and settlement, but can also be caused by natural disturbances like wildfire, wind, or flooding. Suburban and rural development commonly change patterns of habitat fragmentation of natural forests, grasslands, wetlands, and coastal areas as a result of adding fences, roads, houses, landscaping, and other development activities (Dale et al. 2000).

Landscape – a large heterogeneous land area (e.g., multiple square miles or several thousand hectares) consisting of a cluster of interacting ecosystems repeated in similar form (e.g., watershed) (Forman 1995, Duerksen et al. 1997).

Land use – the purpose to which land is used by humans (e.g., protected areas, forestry for timber production, plantations, row-crop agriculture, pastures, or human settlement) (Dale et al. 2000).

Local population – set of individuals of a species that live in the same habitat patch and interact with each other; most naturally applied to "populations" living in such small patches that all individuals practically share a common environment (Hanski and Simberloff 1997).

Matrix – the background ecosystem or land use type in a mosaic, characterized by extensive cover, high connectivity, and/or major control over the landscape functioning (Forman 1995). For example, in a large contiguous area of mature forest embedded with numerous small disturbance patches (e.g., timber harvest patches or clearcut areas), the mature forest constitutes the matrix element type because it is greatest in areal extent, is mostly connected, and exerts a dominant influence on the associated species and ecological processes (McGarigal 2003).

Metapopulation – a network of semi-isolated populations with some level of regular or intermittent migration and gene flow among them, in which individual populations may be extinct but then be recolonized from other subpopulations (Meffe and Carroll 1997).

Mosaic – a pattern of patches, linear corridors, and matrix in a landscape (Forman 1995).

Minimum viable population - The minimum viable population size is the smallest number of individuals required to maintain a population over the long-term (Forman 1995).

Non-native (or exotic) species – organisms (plants, animals, insects, and microorganisms) that occur in locations beyond their known historical, natural ranges or have been brought in from other continents, regions, ecosystems, or habitats (National Invasive Species Council 2001).

Patch – a relatively homogeneous type of habitat that is spatially separated from other similar habitat and differs from its surroundings (Forman 1995).

Remnant patch – habitat patches that escape disturbance (e.g., development) and are left remaining from an earlier more extensive span of habitat (e.g., woodlots in an agricultural area) (Dramstad et al. 1996).

Scale – the relative size or degree of spatial resolution of an area of interest. Small areas of interest (e.g., area around a house of single subdivision) are considered to be fine scale; in contrast to a larger area (e.g., a county or watershed), which is considered to be of coarse scale (Forman 1995, Duerksen et al. 1997).

Suitable habitat – habitat that meets the survival and reproductive needs of a species, allowing for a stable or growing population over time (Lamberson et al. 1994).

THRESHOLDS FOR LAND USE PLANNING: ADDRESSING HABITAT FRAGMENTATION

Varying shapes and configuation of habitat patches resulting from habitat fragmentation, Buchanan, Alabama. Courtesy of John R. Tolliver, USDA Forest Service, www.forestryimages.org.

Habitat fragmentation severely threatens biodiversity and ecosystem functioning wherever humans dominate the landscape. Land use planners play a significant role in determining whether and how landscapes and ecosystems are fragmented or maintain natural connectivity.

Habitat fragmentation is the process whereby contiguous natural areas are reduced in size and separated into discrete parcels. Fragmentation results from a reduction in the area of the original habitat due to land conversion for other uses, such as residential and commercial development. It also occurs when habitat is divided by roads, railroads, drainage ditches, dams, power lines, fences or other barriers that may prohibit the free movement and migration of plant and animal species (Primack 1993, Forman 1995). When habitat is destroyed, a patchwork of habitat fragments is left behind, often resulting in patches that are isolated from one another in a modified and inhospitable landscape matrix.[10] Fragmentation causes the microclimate to be altered due to changes in solar radiation, wind, and humidity; habitat patches become more isolated with a growing distance between remnant patches; and the resulting landscape is modified by changes in size and shape of the resulting patches (Saunders et al. 1991). These changes have varying impacts on species persistence and ecosystem sustainability.

Groups of organisms respond differently to habitat fragmentation. Some species, such as game species like white-tailed deer and bobwhite quail (referred to as edge species), may actually thrive under altered conditions (Bolger et al. 1997). However, many other species—often rare species and habitat specialists—are negatively affected. Species that depend upon the interior of forests, prairies, wetlands or other natural habitats will be absent from landscapes that lack sufficient natural areas containing true core habitat (Meffe and Carroll 1997). Although a fragmented landscape may enhance the abundance of certain generalist species, overall, fragmentation threatens the maintenance of biodiversity and the functioning of natural systems (Soulé 1991, Forman 1995).

To the detriment of many species, particularly those that are area-sensitive, habitat patches may lack the range of resources necessary to support permanent populations (Primack 1993, Forman 1995). Habitat fragmentation will reduce the foraging and nesting ability of animals and can lead to the rapid loss of species due to the creation of barriers to dispersal and colonization. In a fragmented landscape, normal dispersal will be disrupted when the land surrounding the remaining patches is inhospitable to species formerly thriving in the contiguous habitat (e.g., because it is degraded or is home to predators). For example, many bird species that dwell in the forest interior will not cross even short distances of open areas (Askins 1995). When species migration and dispersal is limited, new immigrants are less likely to supplement diminishing populations, thereby, increasing extinction vulnerability (Askins 1995).

The negative effects of habitat fragmentation are compounded by an altered physical environment (*see* "Edge Effects"). Land conversion and land transformation can cause major alterations in hydrologic regimes, mineral and nutrient cycles, radiation balance, wind and dispersal patterns, and soil stability (Harris 1984 as cited in Collinge 1996; Hobbs 1993 *as cited in* Forman 1995). Changes in such ecosystem properties and processes in turn affect native species composition, abundance, and long-term persistence, further degrading the biodiversity and the integrity of the affected natural areas.

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[10] Matrix is the background ecosystem or land use type in a mosaic, characterized by extensive cover, high connectivity, and/or major control over the landscape functioning (Forman 1995) (see Box 2).

UNDERSTANDING THE EFFECTS OF FRAGMENTATION

Over the past 25 years, the scientific community has devoted much energy to understanding the various components of fragmentation—the influence of fragment size, shape, configuration, heterogeneity, connectivity, among other factors—and how they effect the sustainability and persistence of species and natural processes in a landscape. Ideally, scientists would understand the influence and interaction of these characteristics on the continued survival of species and the integrity of ecosystems. Due to gaps in scientific knowledge, available information was only found within the literature to present potential threshold responses related to patch area, proportion of suitable habitat, edge effects, and buffers.

This paper provides land use decisionmakers with concrete information culled from the scientific literature in order to translate the land use guideline #5 offered by the Ecological Society of America (*see* Box 1) for on-the-ground practice. Recommendations on "how to retain large contiguous or connected areas that contain critical habitat" are presented, with specific information on how to best protect habitat patches and sufficient natural area, to minimize edge effects, and to design riparian buffers and habitat corridors.

HABITAT PATCHES

A common consequence of land development is the fragmentation of an originally connected natural landscape into a mosaic of disconnected habitat patches.[11] The size of the remaining habitat fragments significantly influences the type, abundance, and diversity of species that can persist in the affected region. In general, large patches better sustain wildlife populations and ecosystem functions over time than small patches. Holding other factors constant—such as patch shape, condition, and configuration—larger areas of habitat tend to support larger population sizes and a greater number of interior, specialist, and native species due to increased habitat diversity and more core area (Harris 1984, Dramstad et al. 1996, Forman 1995). The probability of a species population being extirpated generally increases with decreasing patch size.[12] This is due to the tendency of larger patches to retain a greater array of the natural resources and ecological functions provided by healthy ecosystems than smaller patches with more edge, increased susceptibility to invasion by exotics or predators, and more disturbed conditions (Soulé 1991, Metro 2001) (*see* "Edge Effects"). Area-sensitive forest bird species in the mid-Atlantic United States, for example, have been found to exhibit lower species diversity and higher extinction and turnover rates in landscapes with smaller mean forest patch size (Boulinier et al. 2001).

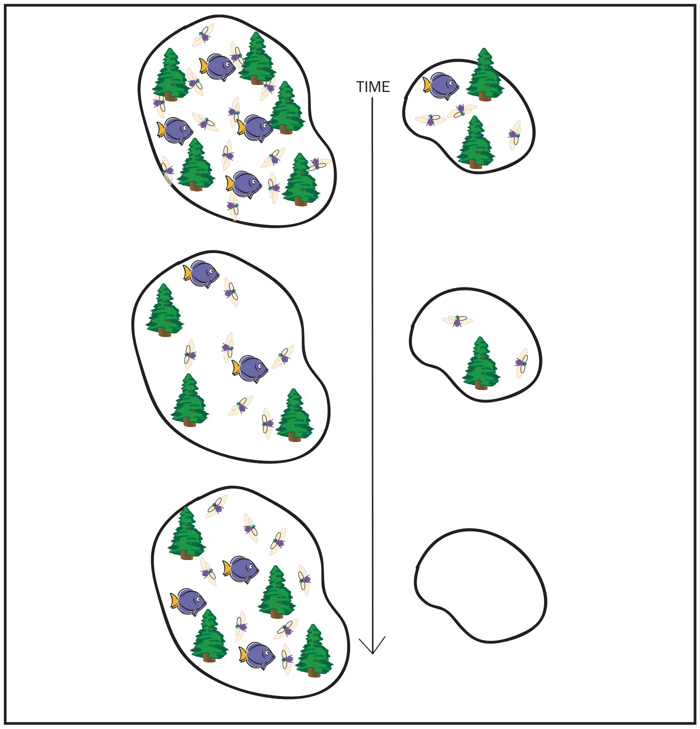

Diagram 2. Patch size and local extinction. *Probability of a local species population going extinct increases with decreasing habitat patch size. A larger patch generally supports a larger population size for a given species than a smaller patch, making it less likely that the species will go locally extinct in the larger patch. Modified from Dramsted et al (1996), Landscape Ecology Principles in Landscape Architecture and Land-Use Planning, p. 20.*

In general, to ensure the survival of individual species, population levels must remain large enough to protect against extinction from random natural events (e.g., floods, fires, droughts) and to maintain sufficient genetic variation to adapt to changing environmental conditions (e.g., changes in rates of predation, competition, disease, and food supply) (Gilpin and Soulé 1986, Meffe and Carroll 1997). A common tool used to determine the size of a population(s) needed to ensure long-term survival is a Population Viability Analysis (PVA). A PVA uses quantitative methods to predict the likely future status of a population or set of populations of conservation concern—often those that are at risk of extinction (Morris et al. 2002). This technique can take into account the many environmental, demographic, and genetic variables that determine extinction probabilities for individual species (Meffe and Carroll 1997).

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[11] A patch is a relatively homogeneous type of habitat that is spatially separated from other similar habitat and differs from its surroundings (Forman 1995).

[12] What is being discussed in this report is to the local extinction of a species population from a particular habitat or region (termed extirpation or population extinction), rather than the overall elimination of the species worldwide (termed global extinction).

Because plant and animal population size is the best predictor of extinction probability, habitat patches should be large enough to maintain viable populations of important species—including rare, endangered, and economically important species—and to maintain the ecological processes that support these communities. Based on Population Viability Analyses, general guidelines have been proposed for minimum viable population sizes:[13] 1) populations less than 50 individuals being too small and vulnerable to extinction due to their rapid loss of genetic variability and inability to withstand natural catastrophes; and 2) populations of 1,000 to 10,000 individuals being adequate to ensure long-term persistence (Meffe and Carroll 1997). Such numbers, however, should be viewed with scrutiny because much debate still exists about what size constitutes a minimum viable population for the many different species that make up natural systems (Saunders et al. 1991).

MANAGING FOR ADEQUATE HABITAT PATCH SIZE

For purposes of this review, minimum patch area is the smallest habitat patch that should be protected in order to sustain a species, a diversity of species or communities, or functioning of ecosystems. The literature suggests that, depending on the species or habitat in question, minimum critical patches range from as little as 0.0004 hectares (0.001 acres) (based on the needs of certain invertebrates) up to 220,000 hectares (550,000 acres) (based on the needs of certain mammals) to sustain target species or communities (*see* Appendix B). This wide range reveals that a generic "minimum" critical patch size or habitat requirement does not exist; thresholds are entirely dependent on the target species in question.

Ultimately, the amount of habitat necessary to maintain healthy wildlife populations varies according to many factors, such as taxonomic group, body size, foraging and resource requirements, and dispersal patterns of the species (Bender et al. 1998). Taxonomic groups, such invertebrates and plants, which have smaller dispersal ranges and tend to respond to their environment at smaller spatial scales, are reported to need less habitat area (e.g., less than 10 hectares or 25 acres) (McGarigal and Cushman 2002).

Larger patch areas are recommended to support bird, mammal, and fish species. Minimum habitat requirements for birds ranged from one hectare up to 2,500 hectares (6,250 acres), with the majority (75 percent) of the values found within the literature to be under 50 hectares (125 acres).[14] Minimum patch size required by mammals ranges from one hectare to 10 hectares for small mammals and up to 220,000 hectares for large-bodied or wide-ranging mammals (e.g., bears, cougars). Larger bodied vertebrates and wide-ranging predators tend to require larger territories to meet resource and reproductive needs (Soulé 1991). Minimum habitat area is greater for predators, such as bears, with recommended patch sizes greater than 900 and 2,800 hectares and cougars with 220,000 hectares (Mattson 1990, Mace et al. 1996, Beier 1993, respectively).[15] In contrast, estimates for habitat requirements for small mammals, such as rodents and rabbits, varied from one hectare to 10 hectares (Soulé et al. 1992, Barbour and Litvaitis 1993, Bolger et al. 1997). Only one study was found to provide evidence on possible watershed area needed to sustain fish species, finding that suitable patch sizes larger than 2,500 hectares might increase the chance of bull trout occurrence in Idaho (Rieman and McIntyre 1995).

Overall, the majority of the findings in this survey pertain to birds and mammals (*see* "A Closer Look at Habitat Patch Size" in Appendix A for specific information on numbers and trends). Few studies were found to recommend patch sizes to sustain plant, invertebrate, or fish populations. Keeping in mind this sample represents a narrow array of species and habitats, the protection of habitat patches of 55 hectares (137.5 acres) or more appears to capture 75 percent of species requirements reviewed in this select survey (*see* Figure 1). Such minimum land parcels, however, are not likely to capture particularly area-sensitive species, like wide-ranging predators or particularly sensitive interior bird species, found to need habitat patches greater than 2,500 hectares (or about 6,175 acres) (Trine 1998, Mattson 1990, and Beier 1993).

Given the great scientific uncertainty and gaps in the knowledge base on minimum habitat requirements of species and ecosystems, land use planners should adopt a conservative approach. The goal should be to maintain sufficiently large intact and well-connected habitat patches that would support the most area-sensitive species, species of greatest environmental concern (e.g., rare, threatened, or endangered species), or focal species, such as keystone species,[16] link species,[17] or umbrella species.[18] Declines in these groups of organisms may have wide ranging implications, negatively affecting the persistence of other associated species and ecosystems (Dale et al. 2000).

Land use planners should carefully consider the conservation needs of species with large-area or specialized life history requirements or that depend upon a combination of different habitats (e.g., large-ranging predators; interior species, or rare species); these species are likely to survive only in rel-

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[13] The minimum viable population size is the smallest number of individuals required to maintain a population over the long-term (Forman 1995); for example, the size of a population that would have a 95 percent probability of persisting for 100 years (Boyce 1992).

[14] Recommended conservation threshold values are based on the goal of capturing 75 percent of the requirements found for species, communities, and habitats surveyed in this literature review; thus, the third quartile was used by calculating the value for which 75 percent of the threshold values lie below this value (after numerical ranking).

[15] One hectare is equal to approximately 2.5 acres.

[16] Keystone species are species that have greater effects on ecological processes than would be predicted by their abundance or biomass alone (Dale et al. 2000).

[17] Link species are species that exert critical roles in the transfer of matter and energy across trophic levels of a food web or that provide critical links for energy transfer within complex food webs (Dale et al. 2000).

[18] Umbrella species are species that either have large area requirements or use multiple habitats and thus overlap the habitat requirements of other species (Dale et al. 2000).

atively large areas or in very specific habitat types (potentially very small, localized areas), which should be actively targeted for protection (Saunders et al. 1991, Ruggierro et al. 1994, Collinge 1996). To help guide conservation planning, umbrella species (e.g., vertebrate mammals such as cougars and grizzly bears) have been proposed as targets for conservation, because their protection may ensure the protection of other secondary species (Franklin 1993). By protecting areas large enough to maintain viable populations of wide-ranging species, sufficient habitat may be maintained to ensure survival of other species dependent on the same habitat. Land use planning that allows for the persistence of focal species—like rare and endangered species, keystone or umbrella species—may help direct land conservation. Land use planners will need the help of local biologists to identify appropriate focal and area-sensitive species in their region to better implement habitat conservation strategies.

Land use planners should strive to protection and maintain habitat patches larger than 55 hectares (137.5 acres).

Even though protecting large expanses of connected habitat is the ultimate goal, this may not be practicable in the often highly developing landscapes in which land use planners often find themselves working. In these settings, land use professionals should try and conserve what habitat remains and, where possible, work with land management agencies and land trusts to identify potential areas for habitat restoration. Working to conserve even the smallest remaining natural areas is important, particularly in human-dominated landscapes. A series of small- or medium-sized reserves may capture a greater diversity of habitat types, environmental heterogeneity, and biological diversity than the preservation of one large fragment (Tscharntke et al. 2002) (*see* "Role of small patches"). Protecting natural habitats with the greatest conservation significance locally and regionally—regardless of size—is vital to preserving biological diversity and ecosystem services. No matter how small habitat patches may be, they still have ecological and/or aesthetic values, whether providing habitat for small organisms like amphibians or insects; providing green space for recreational activities; helping moderate temperature and provide shade in urban areas; or decreasing run-off from streets, pavements, and other impermeable surfaces.

Other Patch Area Design Considerations

The size of any given habitat patch is only one factor determining whether or not the patch will support species persistence, biological diversity, and ecosystem functions. Other factors to consider are the shape, location/configuration, condition, and boundaries of patches, as well as the role of small habitat patches. The following is general guidance on ways to counteract the negative impacts of habitat fragmentation and habitat loss at a landscape scale.

- **Patch shape:** Patch size and shape determine the distance of the patch's edge to the habitat interior and the amount of core area remaining in any remnant habitat patch (*see* "Edge Effects") (Collinge 1996). Shape determines the edge to interior ratio of a habitat patch, which should be as low as possible to minimize edge effects (Wilcove et al. 1986, Saunders et al. 1991, Collinge 1996). Circular habitat reserves are recommended to minimize contact between the protected core habitat and adjacent environmental or human pressures (Wilcove et al. 1986). In contrast, long, thin remnants have proportionally more edge, and thus, more negative edge effects (Forman and Godron 1981, Saunders et al. 1991).

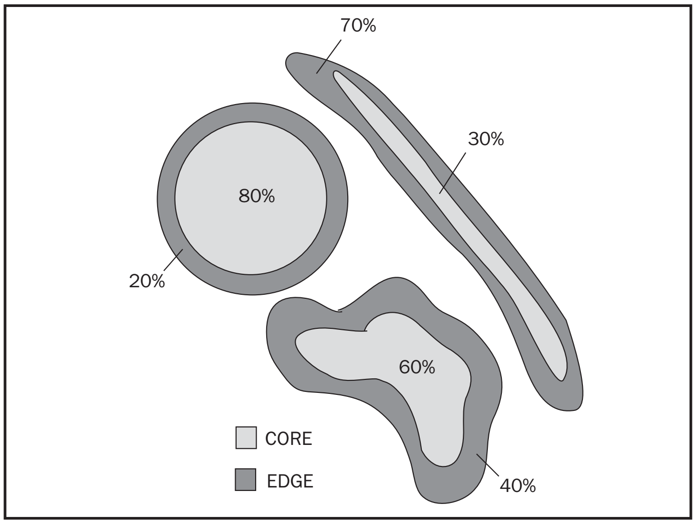

Diagram 3. Patch shape and edge. *The edge to interior ratio of a habitat patch is affected by patch shape. A more convoluted, irregular, or linear patch will have a higher proportion of edge, thus, increasing the number of edge species and decreasing the number of interior species.*

- **Patch location/configuration:** The landscape context in which patches reside may have an even greater effect on the function and sustainability of a habitat fragment than the characteristics of the patch itself (Forman 1995). The distances between suitable habitat patches and the nature of the matrix between these patches will influence species survival (Ruggiero et al. 1994, Andren 1997). In general, more connected habitats are better than isolated habitats because patches in close proximity are likely to enhance species dispersal, recolonization, and persistence (Fahrig and Merriam 1994). Even where wildlife populations may decline or disappear in isolated patches due to random events or patch conditions, recolonization may occur if species are able to successfully disperse from nearby habitat (Pulliam et al. 1992). To maintain demographic linkages, suitable patches should be positioned to provide stop-over points or "stepping stones" for species dispersal (Forman and Godron 1981). The allowable distance between patches will depend upon individual species' dispersal capabilities, which vary within and among species groups (Ruggiero et al. 1994, Bender et al. 1998). When making land use planning decisions, practitioners should consider the contribution of patches to the overall landscape structure and how well the location of any given patch relates or links to other patches (Dramstad et al. 1996).

- **Boundary zone:** The contrast between a patch edge and the surrounding landscape matrix (also referred to as the boundary zone) affects the severity of edge effects and the dispersal abilities of wildlife populations. The higher the contrast between patch types or patches and their surrounding matrix, the greater the edge effects (Franklin 1993). Boundaries in a landscape could be either "hard" or "soft." Hard boundaries usually result from human activities, such as clearcutting and development, and have linear borders with high vegetation contrast, such as between a forest and cultivated field. Soft edges, which dominate natural landscapes, tend to have varying degrees of structural contrast with curved habitat boundaries (Forman 1995). To minimize edge effects at the local scale and facilitate the movement of species between a patch and the surrounding matrix, land use planners should mimic naturally occurring edges and provide gradual thinning of vegetation (e.g., smaller shrubs grading into larger shrubs and taller trees at the edge of a wooded patch) rather than an abrupt transition from vegetated to denuded areas (Forman and Godron 1981, Forman 1995, Duerksen et al. 1997).

- **Patch condition:** The quality of the habitat patch itself will also influence the ability of remnant species and systems to persist or function over the long-term (Fahrig and Merriam 1994, Forman 1995). Large patches with degraded habitat—such as those dominated by non-native species, or with diminished biological diversity, severe erosion, or modified hydrologic patterns—may have less conservation value than small patches of high biological integrity.[19] The biological integrity of land parcels and whether or not they contain unusual or distinctive landscape features (e.g., cliffs, caves, meadows, thermal features, and vernal pools), old-growth forests or mature habitats, or rare, threatened, or endemic species, are also factors that land use planners should consider when selecting which lands to conserve (Dramstad et al. 1996, Duerksen 1997, Lindenmayer and Franklin 2002).

- **Role of small patches:** While large patches generally are recommended to provide sufficient habitat to sustain populations of species—particularly area-sensitive species—small patches also play a vital role in regional conservation. Although larger patches may contain greater habitat diversity than smaller ones, a collection of multiple small patches may capture a greater array of habitats, and perhaps more rare species, than a single large habitat patch (Forman and Godron 1981, Saunders et al. 1991, Forman 1995, Tschartnke et. al. 2002). Small wetlands of less than two hectares, for example, can support surprisingly high species richness of amphibians (Richter and Azous 1995 as cited in Metro 2001). Proximity to core habitat and local habitat heterogeneity, rather than riparian habitat area, may better predict reptile and amphibian richness (Burbink et. al. 1998). In addition, small isolated riparian habitat patches have been found to be vital stop-over sites for en-route migratory birds in the southeastern United States (Skagen et al. 1998). If strategically positioned between larger habitat patches, smaller patches can serve as "stepping stones" to allow for greater species dispersal and recolonization (Murphy and Weiss 1988; Burel 1989 and Potter 1990 as cited in Fahrig and Merriam 1994; Forman 1995).

Many of the above described factors influence not only the effective habitat patch size, but also other fragmentation thresholds, such as the proportion of suitable habitat or the amount of edge in a landscape. Thus, land use planners should keep these design considerations in mind when interpreting the thresholds presented below.

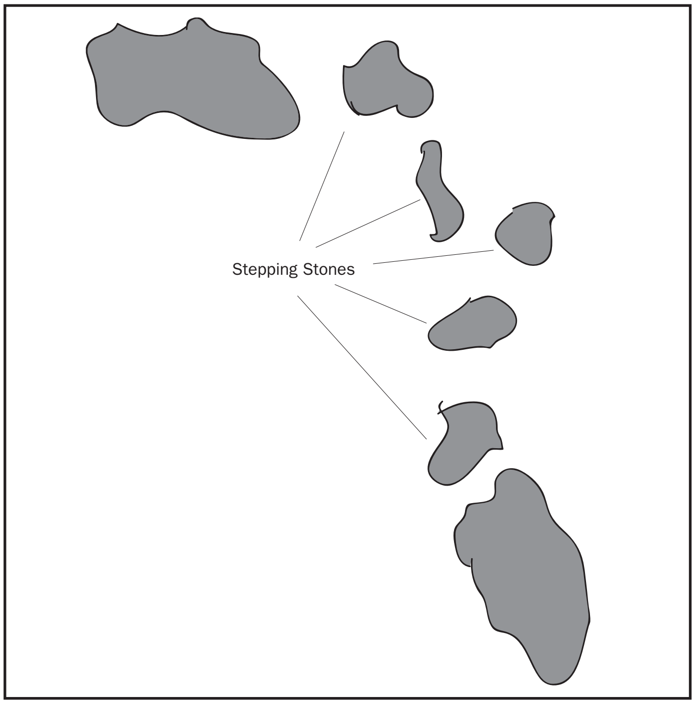

Diagram 4. Stepping stone patches. *Protecting habitat patches strategically positioned between larger habitat patches can be a way to enhance species dispersal and colonization in a landscape, and to increase local species population persistence. Modified from Duerksen et al. (1997), Habitat Protection Planning: Where the Wild Things Are, p 14.*

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[19] Biological integrity refers to "a system's wholeness, including presence of all appropriate elements and occurrence of all processes at appropriate rates" (as cited in Angermeier and Karr 1994).

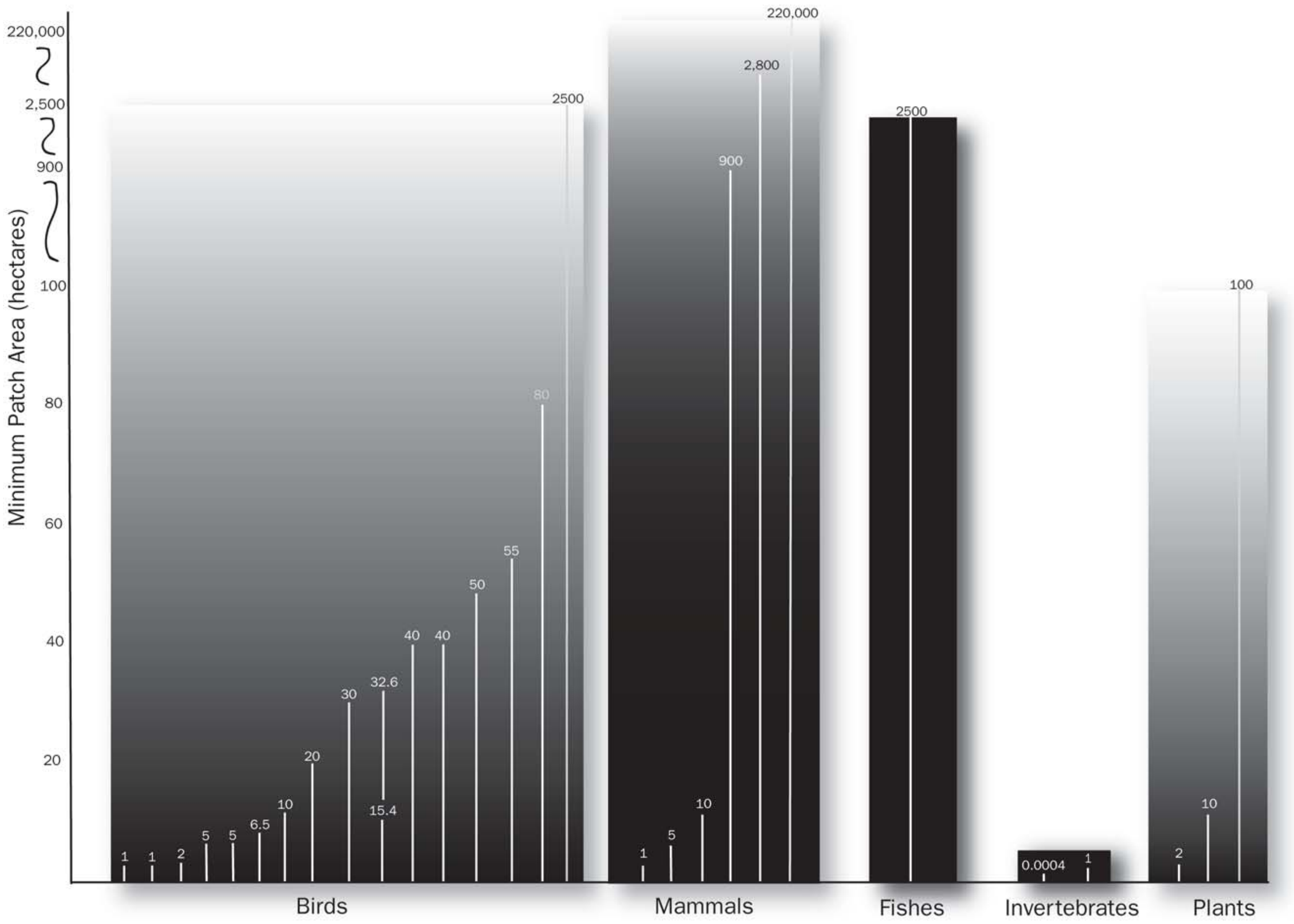

Figure 1. Minimum patch area requirements (in hectares) needed to maintain populations or communities of birds, mammals, fishes, invertebrates, or plants species in the United States, as cited in the scientific literature. Numbers represent the recommended minimum patch area sizes; two numbers along one line indicate a recommended range (*see* Appendix A for specific findings). Lines extend from zero to the recommended minimum patch area sizes to indicate the span of habitat needed for protection.

SUITABLE HABITAT IN LANDSCAPE

Landscapes are complex assemblages of many habitat fragments that together help sustain large-scale biological systems. As a result, meeting minimum patch sizes for species in a given landscape may be inadequate to ensure their persistence (Fahrig 2001). The configuration and nature of the landscape surrounding a patch also greatly determine whether a region will support species persistence and diversity (Lindenmayer and Franklin 2002).

In addition to considering the size of patches, land use planners must consider the total amount of suitable habitat in a given landscape. Local populations of plants and animals are often linked together by dispersal, essentially forming a larger "metapopulation" (Hanski and Simberloff 1997).[20] Individual species from such subpopulations migrate between habitat patches, interacting and breeding with other individuals, which influences the overall survivorship of the species in a region. In addition, the quality and availability of habitat patches can greatly determine the viability of a metapopulation. Some habitat patches may be of higher quality allowing for the local species population to benefit from higher reproductive rates than death rates. These "source" populations produce excess individuals that could emigrate into neighboring patches to settle and breed, thus, expanding the overall population and helping to buffer it from local extirpation. On the other hand, some habitat patches may be of poor quality, where local productivity is less than mortality. Referred to as "sink" populations, these areas lack immigration of individuals from source populations, leading to the extirpation of the local population (Pulliam 1988). For species populations that exhibit a metapopulation structure, land use planners should strive to protect existing source habitat patches, as well as restore habitat that may serve to support future source populations. However, land use planners should be cautious not to designate critical habitat solely by the proportion of the local population present; a source habitat could support as little as 10 percent of the metapopulation, which is responsible for maintaining the other 90 percent of the total population (Pulliam 1988). Rather, land use planners should work with ecologists to identify source habitat by demographic characteristics (e.g., death and birth rates of species).

Metapopulation theory reveals that the local extinction of a subpopulation can be prevented by occasional immigration from neighboring patches, termed the "rescue effect," which is considered important in maintaining small populations and high levels of species diversity (Brown and Kodric-Brown 1977, Stevens 1989). Local extinctions may commonly occur within small habitat patches; about 10-20 percent of certain local populations of plants, arthropods, amphibians, birds, and small mammals within various habitat types have been found to go extinct per year (Fahrig and Merriam 1994). Thus, a set of interconnected habitat patches should be conserved to sustain sufficiently large metapopulations that would allow for regional species persistence.[21] Habitat patches must also be configured to facilitate dispersal and recolonization between patches, particularly those used for breeding and foraging (Saunders et al. 1991, Fahrig and Merriam 1994, Boulinier et al. 2001, Fahrig 2001). Land use planners should strive to identify particular subpopulations, habitat patches, or links between isolated patches that are critical for the maintenance of the overall metapopulation of priority species (Meffe and Carroll 1997).

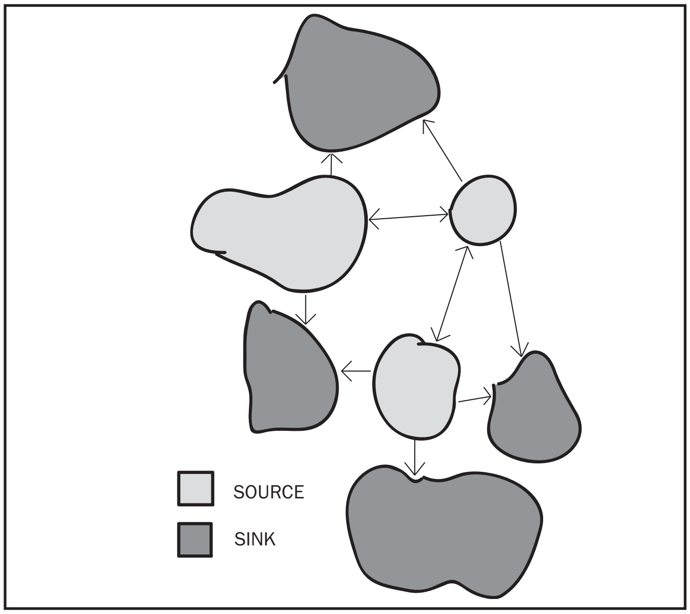

Diagram 5. Metapopulation and Source/Sink Dynamics. *Local populations of organisms in different habitat patches may be linked demographically, forming an interdependent metapopulation. "Source" habitat patches, which supplement local populations in "sink" habitat patches, should be targeted for protection. Ideally, land use planners should protect entire metapopulations. Modified from Mette and Carroll (1994), Principles of Conservation Biology, p 188.*

Not only is the quality of the habitat patches themselves important, but also the condition of the matrix between isolated habitat patches. If the matrix is able to support populations of species present in the original contiguous habitat or allows for adequate species dispersal or migration between fragments, then communities in remnant patches may retain diverse and viable populations of native plants and animals (Askins 1995). Estimating the proportion of suitable habitat in a landscape is a larger scale method of determining how much suitable habitat should be conserved to ensure the persistence of species in a region.

Managing for the Amount of Necessary Habitat in a Landscape

Scientists generally offer recommendations on the proportion of suitable habitat that should be conserved in a

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[20] A metapopulation is a set of local populations that interact by individuals moving between the local populations (or subpopulations) (Hanski and Gilpin 1991).

[21] A local extinction refers to the extinction of a single, local population in a given geographic area; a local extinction does not entail that the entire species has gone extinct within its known range.

landscape based on two scientific trends. First, species disappear in a landscape with the loss of a certain amount of habitat, and different species go extinct at different thresholds of habitat loss (Fahrig 2002). Thus, scientists have estimated extinction thresholds to determine the proportion of suitable habitat needed to sustain specific species.[22] The "extinction threshold" is the minimum amount of habitat required for a population to persist in a region below which the population will go extinct (Fahrig 2001, Fahrig 2002).[23] Extinction thresholds are essentially the converse of population viability estimates derived from PVAs (described above).

Second, threshold values may be based on the amount of habitat below, which the negative effects of habitat fragmentation may compromise species persistence. This is termed "habitat fragmentation thresholds" (Andrén 1994, Fahrig 1998). As the proportion of suitable habitat decreases in a landscape, the reduction in patch sizes and the increasing isolation of these fragments begins to significantly affect the abundance, distribution, or diversity of species in the landscape due to alterations in species movement or the spread of disturbance (e.g., wildfire, flooding, invasion by exotic species), among other factors (Gustafson and Parker 1992, Andrén 1994). The recommendations presented in this review are largely based on existing literature reviews of both extinction thresholds and habitat fragmentation thresholds (*see* Andrén 1994, Fahrig 2001).

Studies of suitable habitat range between 5 percent to 80 percent of the landscape depending on the species, geographic region, and parameters in question (*see* Appendix C). Seventy-five percent of the surveyed studies reported that suitable habitat should be up to 50 percent of the total landscape, whereas 50 percent of the studies reported at least 20 percent of habitat (*see* Figure 2). Given the constraints presented by the available literature (*see* "A Closer Look at Proportion of Suitable Habitat" in Appendix A for explanation on limitations), the conservation of greater proportions of habitat—such as a minimum of 60 percent—is recom-

BOX 3. PLANNING AT THE RIGHT SCALE

Natural communities vary greatly in the area in which they occur. In order to determine which land parcels and how much habitat to protect, land use planners should plan at the appropriate scale for the target system or species. Ideally, planning would occur across multiple scales to capture the greatest habitat and species diversity (*see* Box 2 for a definition of scale).

1. Coarse scale

Certain habitats and species, termed "matrix" habitats and "coarse-scale" species, will require planning to occur at a very large scale to capture their wide-ranging needs. Natural communities—such as spruce-fir forests (Northeast), longleaf pine forests (Southeast), tallgrass prairie (Midwest), and sagebrush (West)—can span as much as one million contiguous acres. Matrix communities are historically dominant habitat and exist across widespread physical gradients, such as broad ranges of elevation, precipitation, and temperature. Coarse-scale species (also termed wide-ranging species) require large areas to access the quantity of habitat or the different habitat types needed for survival (e.g., prairie chicken, fox, badger, marten, and pike minnow). Migratory species (e.g., migratory birds or salmon) and top-level predators (e.g., caribou, wolves, and bears) may depend upon not only matrix communities, but also associated habitat patches (described below), connecting corridors, and aquatic systems. To address the needs of such expansive communities and wide-ranging species, land use planners will need to take a landscape scale and regional approach; an area of several thousand acres up to one million acres may need to be conserved. This scale of planning will likely demand an inter-jurisdictional perspective and inter-municipal cooperation.

2. Intermediate scale

Planning may need to occur at a smaller scale—on the order of several hundred to a thousand acres—to conserve "large patch" community types and "intermediate-scale" species. Occurring in large patches, but not as vast an area as matrix types, are communities like red maple-black ash swamps or northern hardwood forests. Large patch communities may span a thousand acres but are bound by certain physical factors (e.g., coastal salt marshes being defined by low topographic position and predictable tides) or by a single dominant ecological process (e.g., fire, flooding, or drainage). Intermediate-scale species are those that depend on a single large patch or several different kinds of habitats (e.g., amphibians that depend on both wetland and upland complexes).

3. Fine scale

Land use planners will need to plan at a more "fine" or site-specific scale to ensure that "small patch" communities and local-scale species are protected. Small patch communities are communities that naturally occur in narrow, localized, or discrete areas (e.g., fens, bogs, glades, caves, or cliffs) or occur only where specific or narrow physical factors and local environmental conditions are present (e.g., seepages, outcrops, certain types of soil). Local-scale species are species with limited movement and dispersal abilities or specific habitat needs that restrict their populations to a single community or habitat type. Belonging to this category are many rare and threatened species, insects, and plants. Occurrences of small patch communities and local-scale species may be found in only a couple of acres up to several hundred acres.

Given the natural variability in occurrence of communities and species and their wide-ranging geographic needs land use planners will need to plan at multiple scales to capture the biological diversity of a region, as well as to plan at the right scale for designated conservation targets.

The conservation thresholds found within this literature survey are predominately based on matrix and large patch communities, as well as coarse- and intermediate-scale terrestrial species. Thus, the findings and recommendations in this report do not fully address the conservation needs for small patch communities, local-scale species, and aquatic environments. To ensure the protection of restricted communities and rare species, land use planners will need to collaborate with local ecologists to identify priority conservation areas for their region.

The above information is based on research by The Nature Conservancy (TNC) (see Poiani and Richter 2000, and TNC 1998).

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[22] From a species perspective, suitable habitat has been interpreted as habitat utilized for nesting, with associated expected birth and death rates that allow for a stable or growing population (Lamberson et al. 1994).

[23] The extinction threshold may be estimated by: 1) the minimum amount of habitat below which the equilibrium population is zero; or 2) the minimum amount of habitat below which the probability of longterm population survival is less than one (Fahrig 2002).

mended to sustain long-term populations of area-sensitive species and rare species.

Scientists have proposed that more robust species (e.g., large dispersal range, high fecundity, high survivorship)—usually the more common widespread species—may persist in even the most extensively fragmented systems with only 25 to 50 percent of suitable habitat. In contrast, rare species and habitat specialists like the Northern spotted owl may require up to 80 percent of suitable habitat to persist in a region (Lande 1987, Lande 1988, Lamberson et al. 1992). Land use planners should take into account the more sensitive and rare species within their region to develop critical thresholds for proportions of suitable habitat relevant to their geographic setting (Mönkkönen and Reunanen 1999). Such an approach may also provide for the protection of more common and robust species that depend on similar habitat types.

Land use planners should strive to conserve at least 20% to 60% of natural habitat in a landscape.

In addition to the proportion of suitable habitat, other considerations should be factored into land use decisionmaking, such as the spatial arrangements of remaining habitat patches and the matrix between patches. In landscapes that are highly fragmented—including most urban, suburban, and even rural areas with less than 30 percent of remaining suitable habitat—the spatial arrangement of habitat patches greatly affects species survival (Andrén 1994). For example, wetland bird communities are found to depend not only on their local habitat, but also on the amount of wetlands within a surrounding three kilometer buffer (Fairbairn and Dinsmore 2001).

The condition of the surrounding matrix in which habitat patches are embedded also influences the effective size of the remaining fragments and the degree to which the patches are isolated (Andrén 1994, Lindenmayer and Franklin 2002). In turn, these factors affect whether or not species will be able to successfully disperse among habitat patches and whether important ecosystem processes, such as fire and hydrologic cycling, will occur on the landscape (Fahrig and Merriam 1994) (*see* "Patch location/configuration").

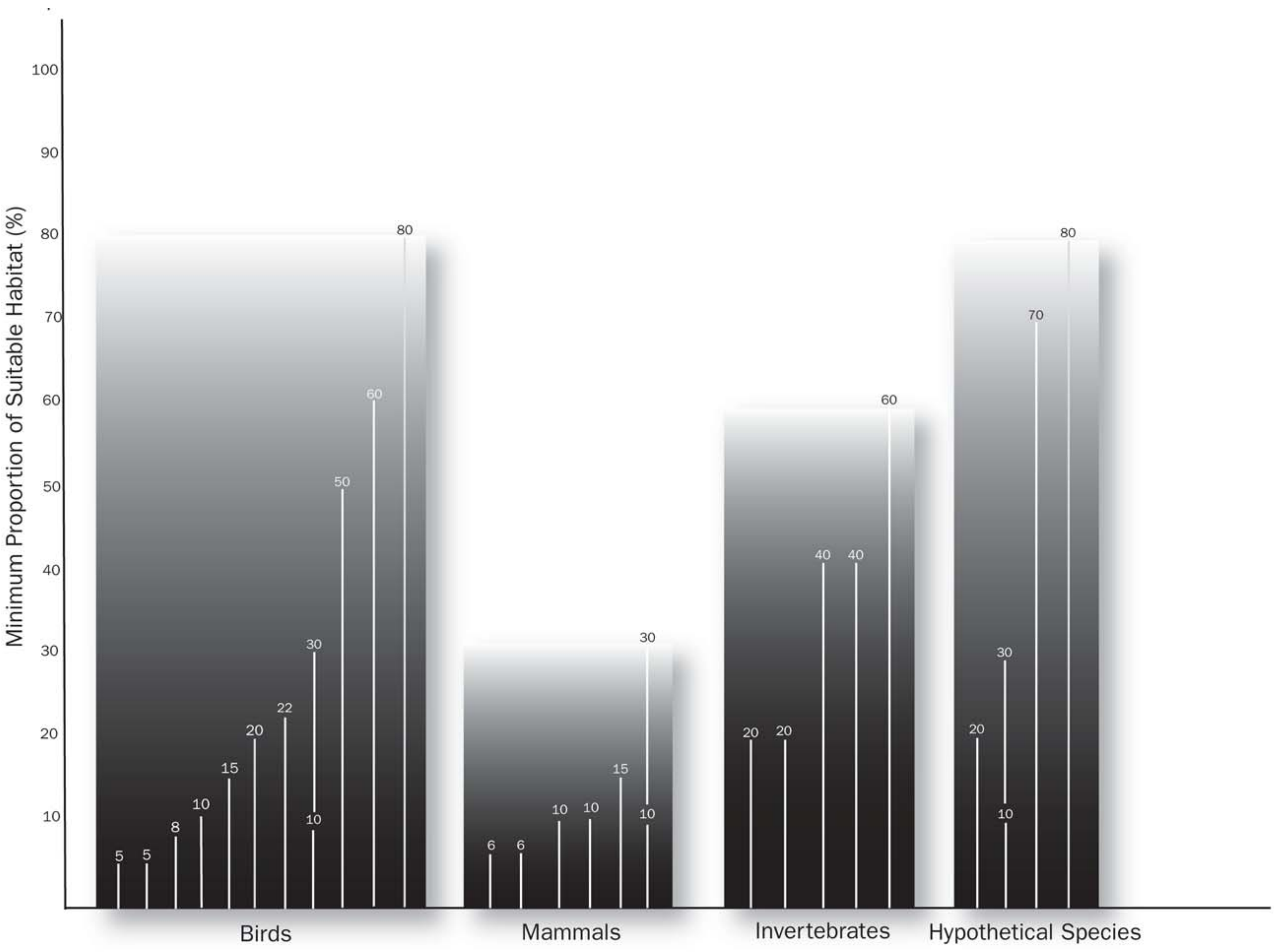

Figure 2. Recommended minimum proportions of suitable habitat (in percentages) needed to maintain populations or communities of birds, mammals, invertebrates, or hypothetical species (as determined by models) in the United States, as cited in the scientific literature. Numbers represent the recommended minimum proportions of habitat; two numbers along one line indicate a recommended range (*see* Appendix B for specific findings). Lines extend from zero to the recommended proportion to indicate the span of habitat needed for protection.

EDGE EFFECTS

Habitat fragmentation inevitably results in the creation of edge environments. Edges occur where a habitat—such as a forest, prairie, or wetland—meets a road, clearcut, housing development, or some other natural or artificial transition or boundary (Soulé 1991). Habitat fragments differ from the original contiguous natural habitat in that they have a greater amount of edge per area and the habitat core is closer to an edge environment. Patch edges may have significantly different conditions than the contiguous system or habitat interior, with altered fluxes of wind, sun exposure, water, and nutrients that greatly affect animal and plant communities (Saunders et al. 1991, Murcia 1995). This change in energy, nutrient, or species flow results from increased amounts of edge and reduced interior habitat, and has been termed the "edge effect."

Increased amounts of edge along habitats create a disturbed environment that allows for the establishment of pest and predator species, which penetrate the fragment interior and adversely affect the diversity and abundance of interior species (Primack 1993). Mammalian predators (e.g., raccoons, foxes, coyotes, feral cats), egg-eating birds (e.g., crows and blue jays), and brood parasitizers (e.g., brown-headed cowbirds) concentrate their hunting along forest edges, thus, increasing the intensities of predation on native species (Soulé 1991).[24] Habitat fragmentation also increases the vulnerability of remnant patches to invasion by exotic and pest species (Soulé 1991, Askins 1995). Higher frequency and intensity of disturbances, like fire and wind damage, may also result due to increased edge (Soulé 1991). Edges like roads and trails introduce such disturbances as pedestrian, pet, and vehicular traffic, causing animals to avoid such areas (Duerksen et al. 1997). Each of these edge effects has significant impact on the vitality and composition of the species in the remaining habitat patch.

Information on environmental and species response to edges helps determine how large patch sizes should be designed to provide sufficient interior habitat, as well as how far development, such as roads, trails, and housing, should be from remnant core areas.

MANAGING FOR EDGE INFLUENCE

The intensity of edge effects has been measured by a number of different methods. The influence of an edge (termed "edge influence") may be defined as the distance between the border to the point where microclimate and vegetation do not significantly differ from the interior conditions of the habitat. From a species perspective, edge influence may be defined as the distance from an edge to the area where species densities, survival rates, or reproductive rates do not differ from those in the interior habitat (Forman 1995, Murcia 1995). Edge influence has also been measured by the behavioral response of animal movement, such as flushing distance, from a disturbance associated with edge environments.[25]


Creation of edge by deforestation, Willamette National Forest, Oregon. Photo courtesy of Steve Holmer, American Lands Alliance.

The intensity of edge effects is influenced by many physical factors, such as the shape and size of the patch, the direction the edge faces (i.e., aspect), and the structural contrast of its boundaries (Soulé 1991). As discussed earlier, larger, circular patches will have more interior habitat and less edge than a rectangular or oblong patch of the same size (Forman and Godron 1981) (*see* "Patch shape"). The orientation of edges affect the amount of exposure to solar radiation, with edges facing the equator tending to have wider edge influence (Forman and Godron 1981, Murcia 1995). The more structurally different the boundaries between different habitat types, the greater the edge effects.

To decrease the influence of edge, buffers are recommended to "soften" the transition between natural and artificial environments (*see* "Boundary zone"). A remnant forest patch directly abutting cropland or urban development will have significant edge effects in contrast to a forest adjacent to a buffer of small shrubs or secondary vegetation. In addition, some habitat types may be more susceptible to negative edge effects; for example, grasslands have been found to exhibit wider edges than forest edges (Forman 1995).

Scientists offer a wide range of findings on the distance edge effects penetrate into ecosystems in the United States, with results ranging from only eight meters up to five kilometers. Based on the response of birds to edge environments, edge effects may penetrate into a habitat patch from about 16 meters up to almost 700 meters; mammals may avoid edge environments from 45 meters up to 900 meters; and microclimate changes may extend from eight meters up to 240 meters into habitat (*see* Appendix E). The majority of the surveyed studies (75 percent) estimates edge influence to be approximately 230 meters or less (*see* Figure 3).

Based on this select review, land use planners should take a conservative approach to mitigating edge effects. To pro-

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[24] Cowbird females lay their eggs in the nests of other bird species, relying on these hosts to incubate and raise their chicks. Brown-headed cowbirds have been found to parasitize over 220 host species. (*see* http://www.audubon.org/bird/research/cowbird-info.html).

[25] Flushing distance is the distance that an animal may flee in response to a disturbance, such as in response to pedestrian or pets on a trail or vehicular traffic on roads (Duerksen et al. 1997)

vide for sufficient suitable habitat, land use planners should buffer remnant patches by at least 300 meters from all edge peripheries, particularly for matrix and large patch community remnants; naturally small patch communities may not require such a wide buffer (*see* Box 3). The area within the buffer should not be counted as suitable habitat provided for species conservation. In addition, roads, trails, and other development should be placed at least 300 meters away from interior habitat to minimize impact. Ideally, land use planners and ecologists should work collaboratively to determine the intensity of edge effects by the response of species or groups of species that are most sensitive to patch size in the ecosystems or regions of concern (Forman 1995). Measuring edge distance by the most sensitive species—often vertebrates of conservation concern—would mean that the influence of edges may actually be hundreds or thousands of meters, thus, requiring much larger patch sizes to meet habitat requirements.

To avoid the negative effects of edges, land use planners should consider buffering up to 230 to 300 meters around edge peripheries.

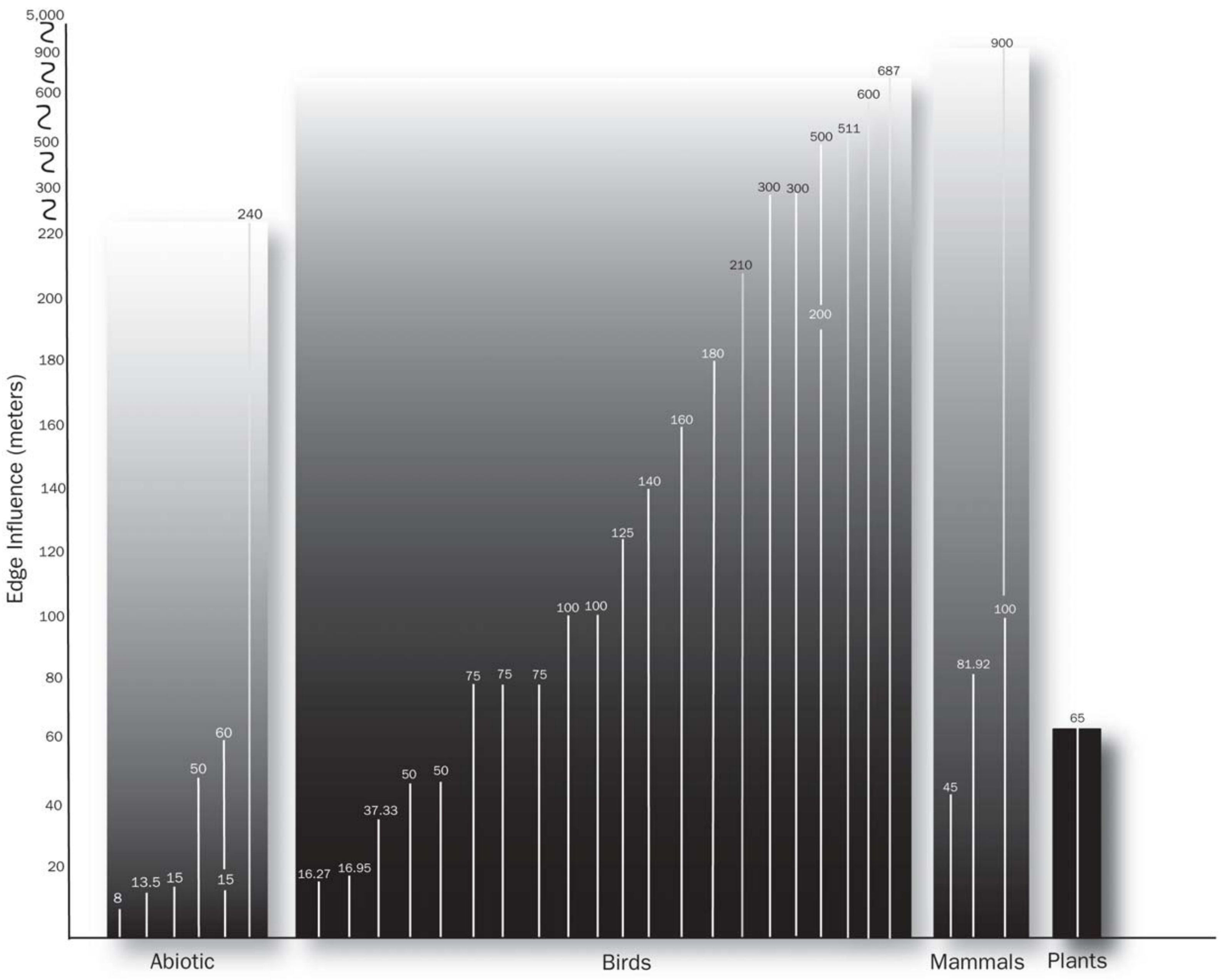

Figure 3. Distances (in meters) that edge effects penetrate into habitats in the United States, as cited in the scientific literature. Edge width is measured by abiotic, bird, mammal, or plant responses; abiotic responses include microclimate changes, such as changes in temperature, humidity and light. Numbers represent edge width distance findings; two numbers along one line indicate a range of edge width distance (*see* Appendix C for specific findings). Lines extend from zero to the determined edge widths to indicate the span of habitat that is affected by edge effects.

RIPARIAN BUFFERS

Although generally comprising a small proportion of the landscape—often less than 1 percent—riparian areas are regional hot spots that support a disproportionately high number of wildlife species and provide a wide array of ecological functions and values (Naiman et al. 1993, Fischer and Fischenich 2000, National Research Council 2002). The support of high levels of species diversity and ecological processes in these areas is due in part to regular disturbance events, like floods, as well as to climatic and topographic variation and the availability of water and nutrients (Naiman et al. 1993).

Riparian areas are ecosystems adjacent to or near flowing water, such as rivers, lakes, shorelines, and some wetlands. They are transitional areas between aquatic and upland terrestrial systems and exhibit gradients in environmental conditions, ecological processes, and living organisms (National Research Council 2002). Unfortunately, riparian systems are continuously threatened by adjacent or upstream human activities. For example, agricultural, industrial, or urban development can increase levels of light, temperature, stormwater runoff, sedimentation, pollutant loading, and erosion, which degrade water quality and diminish suitable aquatic habitat (Castelle et al. 1994). In the last 200 years, over 80 percent of riparian land in North America and Europe has disappeared (Naiman et al. 1993).

To ameliorate the negative impacts of adjacent land uses, a common regulatory and management practice is to establish protected areas, or buffers, around aquatic resources like rivers, streams, lakes, and wetlands. At least 15 states and seven local jurisdictions in the United States have adopted riparian buffer regulations, protecting widths ranging from six meters to over 300 meters in size (Johnson and Ryba 1992).

Buffers are vegetated zones, usually linear bands of permanent vegetation, preferably native species, located between aquatic resources and adjacent areas subject to human alteration (Castelle et al. 1994, Fischer and Fischenich 2000). Buffers can help regulate riparian microclimate and provide necessary shading for the in-stream growth and reproduction of aquatic life; stabilize stream banks and prevent channel erosion; provide organic litter (e.g., leaf litter) and woody debris, which are important sources of food and energy for fish and aquatic invertebrate communities; remove or regulate sediment, nutrients, or other contaminants (e.g., pesticides, herbicides) from runoff; provide flood attenuation and storage to decrease damage to property; and provide wildlife habitat (Castelle et al. 1994, O'Laughlin and Belt 1995, Wenger 1999, Fischer and Fischenich 2000, National Research Council 2002).

Riparian buffer establishment, North Hather Creek, Innoko, Alaska. Courtesy of U.S. Fish and Wildlife Service.

MANAGING FOR ADEQUATE BUFFER WIDTH

Recommended buffer widths are commonly determined by one of two methods: uniform versus variable widths. Uniform-width buffers are commonly adopted because they are easier to enforce, require less specialized knowledge, time, and resources to administer, and allow for greater regulatory predictability (Castelle et al. 1994). Uniform widths are often based on a single resource protection goal, usually related to water quality. In contrast, with variable-width buffers, the size or width of the strip is adjusted along its length to account for multiple functions, adjacent land use, and site and stream conditions. The width of the strip may be adjusted depending on the value of the aquatic resources, the intensity of surrounding land use, and the type and condition of vegetation, topography, soils, or hydrology, among other variables. For example, a larger width may be required for buffers surrounding more pristine or highly valued wetlands or streams; in close proximity to high impact land use activities; or with steep bank slopes, highly erodible soils, or sparse vegetation (Castelle et al. 1994, Fischer and Fischenich 2000).

Land use planners should strive to establish 100-meter wide riparian buffers to enhance water quality and wildlife protection.

Although the method of varying buffer width is generally believed to provide more adequate protection for aquatic resources, it may be less efficient because variable strips can retain less material than a uniform-width buffer of equivalent average width (Weller et al. 1998). Thus, providing policymakers with scientific guidance on uniform buffer widths allows for the implementation of practicable land management practices that protect aquatic resources.

For this report, riparian buffer widths are measured from the top of the bank or level of bankfull discharge of one side of a water body;[26] therefore, a 50 meter buffer on a 10 meter stream would create a zone at least 110 meters wide (Wenger 1999, Fischer and Fischenich 2000).

As with other conservation thresholds, the scientific literature does not support an ideal buffer width applicable in all circumstances. This survey found recommended buffer widths ranging from one meter up to 1600 meters, with 75 percent of the values extending up to 100 meters (*see* "A Closer Look at Buffer Width" in Appendix E for further discussion). At minimum, a riparian buffer should encompass "the stream channel and the portion of the terrestrial landscape from the high water mark towards the uplands where vegetation may be influenced by elevated water tables or flooding, and by the ability of soils to hold water" (Naiman et al. 1993).

The necessary buffer size varies considerably based on the specific management goal. In general, recommended buffer sizes are significantly greater if the intent is to protect ecological functions, such as providing wildlife habitat and supporting species diversity, as opposed to water quality functions.

Based on the majority of scientific findings, land use practitioners should plan for buffer strips that are a minimum of 25 meters in width to provide nutrient and pollutant removal; a minimum of 30 meters to provide temperature and microclimate regulation and sediment removal; a minimum of 50 meters to provide detrital input and bank stabilization; and over 100 meters to provide for wildlife habitat functions.[27] To provide water quality and wildlife protection, buffers of at least 100 meters are recommended (*see* Figure 4).

OTHER BUFFER DESIGN CONSIDERATIONS

The width of any given buffer is just one aspect, albeit important, which determines its ability to provide a variety of functions. Other factors to consider are the linear extent, vegetation composition, and level of protection of buffers. The following is general guidance on the design and development of buffers.

- **Vegetation:** Buffers should have diverse vegetation that is both native and well-adapted to the region. Maintaining a diverse array of species and vegetation structure (e.g., herbaceous ground cover, understory saplings, shrubs, and overstory trees) is recommended to allow for greater tolerance to possible fluctuations in environmental conditions (e.g., water levels, temperature, herbivory), and to provide for greater ecological functions (e.g., wildlife habitat) (see Fischer and Fischenich 2000 for further guidance on vegetation type, diversity, and propagation techniques).
- **Extent:** In part, the effectiveness of a buffer in meeting management objectives is a function of the linear extent of the aquatic system that is protected (Wenger 1999). Protection efforts should prioritize the establishment of continuous buffer strips along the maximum reach of stream, rather than focusing on widening existing buffer fragments (Weller et al. 1998). Protection of the headwater streams as well as the broad floodplains downstream is also recommended. Headwater streams and downstream floodplains generally encompass less than 10 percent of total landmass; thus, this level of protection is practicable (Naiman et al. 1993). Ideally, buffers

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[26] The bankfull discharge is the maximum level of discharge that a stream channel can convey without flowing onto its floodplain. This stage plays a vital role in forming the physical dimensions of the channel because the flows near the bankfull stage move the most sediment over the long-term and the processes of sediment transport and deposition are the most active in forming the channel (Dunne and Leopold 1978).

[27] While a 100-meter buffer is recommended to provide for adequate wildlife values, some natural riparian habitat is too narrow to support such an area. In these cases, land use planners should consider the utility of narrower buffers, especially where they might function as wildlife corridors (see "Habitat Connectivity").

should extend along all perennial, intermittent, and ephemeral streams, lakes, shorelines, and adjacent wetlands (Weller et al. 1998, Wenger 1999), so long as such buffering would not create detrimental upland habitat fragmentation as might be the case in areas of high stream densities (Lindenmayer and Franklin 2002).

- **Buffer protection:** To ensure that buffers function adequately, all major sources of disturbance and contamination should be excluded from the buffer zone, including dams, stream channelization, water diversions and extraction, heavy construction, impervious surfaces, logging roads, forest clear cutting, mining, septic tank drain fields, agriculture and livestock, waste disposal sites, and application of pesticides and fertilizers (Wenger 1999, Pringle 2001). Another consideration is the level of legal protection afforded to the area. Whether the buffer is in preservation status or protected under a conservation easement that allows for some level of activity, for example, will also determine its ability to provide desired functions.

BOX 4. UNDERSTANDING THE EFFECTS OF LAND USE

The many different uses of land—whether for agriculture, silviculture, recreation/open space, or commercial or residential development—will have varying impacts on the ecosystems, habitats, and species in a region. The types, extent, and combinations of land uses within a matrix will affect the viability of habitat patch sizes, the amount of suitable habitat, the severity of edge effects, and the utility of buffers and corridors in a given landscape.

Certain land use types are likely to be more compatible with biodiversity conservation in certain landscapes, depending on the natural arrangement of physical features, habitats, and species, and the effect of previous land uses (Forman 1995). A study on breeding bird communities in central Pennsylvania, for example, found that forests within agricultural landscapes had fewer forest-associated species, long-distance migrants, forest-canopy and forest-understory nesting species, and a greater number of edge species than forest landscapes primarily disturbed by silviculture, irrespective of the effect of disturbance (Rodewald and Yahner 2001). In Colorado, ranchlands and protected reserves were found to be more compatible with species of conservation concern (including songbirds, carnivores, and plant communities) than exurban developments, which tended to support only human-adapted species (Maestas et al. *in press*).

To plan for long-term sustainability, land use planners will need more guidance on the level of compatibility of different land uses in various regions and ecosystems. As a general rule, a landscape mosaic should be planned first according to its ecological constraints (e.g., water availability, forest and soil productivity, natural flooding/fire cycles) and natural site potential (e.g., natural potential for productivity and for nutrient and water cycling) (Dale et. al. 2000). In terms of hierarchical planning, a general recommendation is for land use planners to first plan “for water and biodiversity; then for cultivation, grazing, and wood products; then for sewage and other wastes; and finally for homes and industry” (Forman 1995 *as cited in* Dale et al. 2000, p.658).

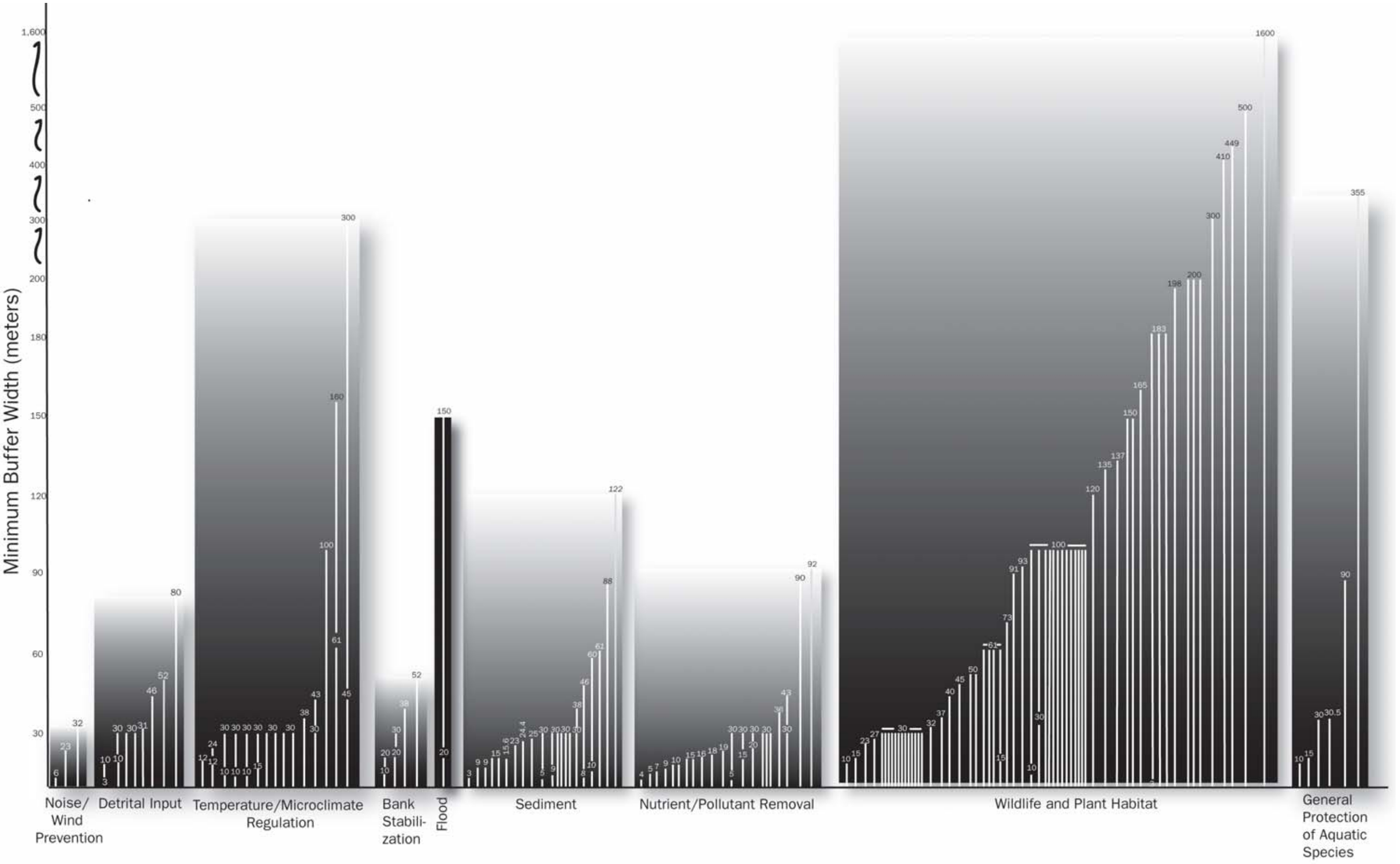

Figure 4. Recommended minimum riparian buffers (in meters) from each side of a water body (e.g. stream bank) needed to prevent noise/wind damage; provide detrital input; moderate temperature/microclimate; stabilize banks; provide flood attenuation; control sediment; reduce nutrients/pollutants; and provide wildlife habitat functions and general protection of aquatic systems in the United States, as cited in the scientific literature. Numbers represent the recommended minimum buffer widths; two numbers along one line indicate a recommended range (*see* Appendix D for specific findings). Lines extend from zero to the recommended buffer widths to indicate the span of habitat needed for protection.

HABITAT CONNECTIVITY

Conservation biologists generally agree that species viability and diversity are enhanced by well-connected habitats (Fahrig and Merriam 1985, Gilpin and Soulé 1986, Primack 1993, Noss and Cooperrider 1994, Meffe and Carroll 1997, Beier and Noss 1998, Lehtinen et al. 1999). Because small, isolated reserves are unlikely to maintain viable populations over the long-term, and because climate change and disturbances require that organisms be able to move over large distances, corridors are recommended as one conservation measure to counter the negative effects of habitat fragmentation and patch isolation (Noss 1991).

Not only can riparian buffers help ensure water quality protection and habitat for plants and animals adjacent to waterbodies, but they can also act as dispersal routes for species and connect remnant patches.[28] Although riparian corridors are useful for some terrestrial wildlife, linkages outside riparian areas may be required to maintain connectivity for non-associated upland species (McGarigal and McComb 1992).

Corridors (also referred to as conservation corridors, wildlife corridors, or dispersal corridors) are intended to permit the direct spread of many or most taxa from one region to another (Brown and Gibson 1983 *as cited in* Noss 1991). They should facilitate foraging movements, seasonal migrations, dispersal and recolonization, and escape from disturbance (Saunders et al. 1991, Soulé 1991). Whether or not corridors actually provide connectivity will depend largely on the species in question and its dispersal capabilities and movement patterns across the landscape (Saunders et al. 1991). Given the species-specific nature of this issue, generalizations about the biological value of corridors are under debate among the scientific community (Noss 1987, Simberloff and Cox 1987, Simberloff et al. 1992, Franklin 1993, Beier and Noss 1998) (for further discussion *see* Appendix A "Further Analysis").

MANAGING FOR OPTIMAL CORRIDOR WIDTH

An important design consideration when maintaining or establishing habitat corridors is width. Corridor width can influence the dispersal behavior of species, resulting in changes in home range size, shape, and use. In addition, corridor width is positively correlated with the abundance and species richness for birds, mammals, or invertebrates (Lindenmayer and Franklin 2002). As is true for other conservation thresholds, in general, the wider the better. Wider corridor bands are recommended to provide interior habitat conditions, which allows for the movement and/or habitation of interior species. In addition, greater habitat area is more likely to provide sufficient cover for species from predators, domestic animals, or human disturbance (Forman and Godron 1981). Corridors that are too narrow may consist entirely of edge, thus, deterring the use by interior or area-sensitive species or causing an increase in mortality from predation (Wilcove et al. 1986).

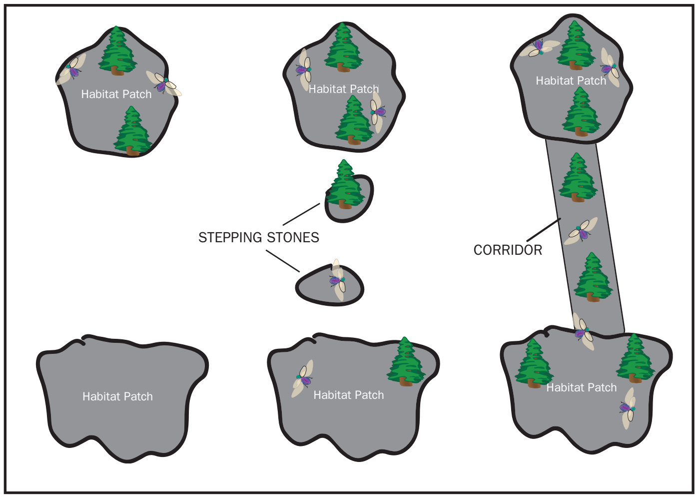

Diagram 6. Habitat Connectivity. *Habitat connectivity can be increased by the protection of stepping stone patches or by the establishment of a corridor. Modified from Dramsted et al. (1996), Landscape Ecology Principles in Landscape Architecture and Land-Use Planning, p. 37.*

Although corridor width has been identified as an important design element, few studies explicitly examined minimum corridor width requirements. This survey found a limited number of studies that provide indirect evidence on effective corridor sizes, however, none of the reviewed studies explicitly tested different corridor widths with the goal of determining an optimal size. Although they did not directly examine recommended corridor width, three studies did find corridor widths of 32 meters and 100 meters to encourage the movement of butterflies and reduce species turnover rates for breeding birds, respectively (Haddad and Baum 1999, Haddad 1999 for butterflies; Schmiegelow et al. 1997 for birds).

Data limitations on the relationship between corridor width and species response prevent the development of recommendations on optimal corridor size. For any given set width, corridor effectiveness will vary with other attributes, such as length, habitat continuity, habitat quality, and topographic position in the landscape, among other factors (Lindenmayer and Franklin 2002) (*see* "Other Corridor Design Considerations").

First and foremost, land use planners should strive to limit the degree of isolation between existing habitat patches and optimize the natural connectivity to allow for the dispersal of sensitive native species through the most appropriate means. This may be done by establishing habitat corridors, maintaining specific structural conditions within the landscape, or setting aside stepping stone patches (Lindenmayer and Franklin 2002) (*see* "Inter-patch distance").

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[28] A riparian corridor is a strip of vegetation adjacent to an aquatic system that connects two or more larger patches of habitat through which an organism is likely to move (Fischer et al. 2000). Corridors are not only riparian but also can be positioned in upland environments as well.

Simultaneously, land use planners should minimize the connectivity of artificial habitats like clearcuts, agricultural fields, and roadsides that tend to spread exotic and pest species (Noss 1991).

OTHER CORRIDOR DESIGN CONSIDERATIONS

Corridor width is one important factor that determines whether a corridor will enhance landscape connectivity. Other factors to consider are the condition of the landscape matrix, the distances between remnant patches, and the extent and configuration of the corridors themselves.

- **Condition of landscape matrix:** The landscape matrix in which corridors are embedded greatly influences corridor use. If conditions in the matrix are suitable (e.g., sufficient original vegetation cover exists), then species reliance on corridors may be minimized. On the other hand, if matrix conditions are inhospitable or degraded (e.g., are highly developed or fragmented; have disrupted ecological processes or disturbed conditions; or are highly invaded by exotic species), then corridor systems linking remnant patches may be required to retain landscape connectivity (Rosenburg et al. 1997 *as cited in* Lindenmayer and Franklin 2002). Given that land use planners often work in extensively developed or developing areas, the latter case is the most likely. Understanding the relationship between the landscape matrix and the movements of target organisms will be fundamental in determining the best placement of corridors to enhance connectivity (Lindenmayer and Franklin 2002).

- **Inter-patch distance:** The distance between remnant patches will affect the conservation value of corridors. When distances between remnant patches are short as compared to the movement ability of target species, a stepping stone approach may be the most effective mechanism for promoting dispersal (*see* "Patch location/configuration"). On the other hand, if the distance separating habitat fragments is relatively far, corridors may be the right mechanism to provide landscape connectivity (Haddad 2000).

- **Corridor configuration and extent:** Networks of intersecting corridors may provide for more effective migratory pathways, allowing greater opportunities for animal foraging and predator avoidance (Forman and Godron 1981). Ideally, a corridor would "encompass the entire topographic gradient and habitat spectrum from river to ridgetop" (Noss 1991). Such an expansive corridor network may allow for the representation of different native habitat and land cover types in a region. In addition, having such a broad system of corridors would help enhance overall resiliency in case of the destruction of individual corridors by unexpected disturbances (Noss 1991).

BOX 5. CONSERVATION THRESHOLDS: A STARTING POINT

The following summarizes findings from a select sample of scientific papers pertinent to species and ecosystems in the United States on critical thresholds related to minimum habitat patch area, proportion of suitable habitat, edge influence, and riparian buffer width. Recommendations are based on the goal of capturing 75 percent of the requirements found for species, communities, and habitats surveyed; thus, the third quartile was used by calculating the value for which 75 percent of the threshold values lie below this value (after numerical ranking). These guidelines should be interpreted very cautiously because they are based on a small sample, and may not be applicable for specific species, habitats, and geographic settings of concern. Land use planners and land managers should consider these results as a baseline from which to launch more tailored and in-depth assessments.

Habitat Patch Area

In general, land use planners should strive to maintain and protect habitat patches greater than 55 hectares (137.5 acres). The goal should be to maintain larger parcels greater than 2,500 hectares (or about 6,175 acres) to protect more area-sensitive species.

Proportion of Suitable Habitat

In general, land use planners should strive to conserve at least 20 percent up to 50 percent of the total landscape for wildlife habitat, where possible.[‡] The conservation of greater proportions of habitat—such as a minimum of 60 percent—may be needed to sustain long-term populations of area-sensitive species and rare species.

Edge Influence

In general, to avoid the negative effects of edges on habitats, land use planners should consider establishing buffer zones up to at least 230 to 300 meters from the periphery of edges.

Riparian Buffer Width

In general, land use planners should plan for riparian buffer strips that are a minimum of 25 meters in width to provide for nutrient and pollutant removal; a minimum of 30 meters to provide temperature and microclimate regulation and sediment removal; a minimum of 50 meters to provide detrital input and bank stabilization; and over 100 meters to provide for wildlife habitat functions. To provide water quality and wildlife protection, buffers of at least 100 meters are recommended.

Landscape Connectivity

Land use planners should strive to reduce the distances between habitat patches and to optimize the natural connectivity of the landscape. This may be done by establishing habitat corridors that connect previously isolated patches; by maintaining the natural, structural conditions within the landscape; or by setting aside stepping stone patches. Simultaneously, land use planners should minimize the connectivity of artificial habitats like clearcuts, agricultural fields, and roadsides.

[‡] The 50 percent recommendation is based on capturing 75 percent of the threshold values surveyed; 20 percent is based on capturing 50 percent of threshold values surveyed. The latter recommendation is provided because land use planners are often working in highly developed regions where protecting 50 percent or more of the landscape is impractical.

RECOMMENDATIONS FOR FUTURE RESEARCH AND ACTION

THE ROLE OF THE SCIENTIFIC COMMUNITY

More scientific research is needed to help inform specific land use decisions being made everyday in the United States—decisions that significantly determine the future of domestic biodiversity. This survey of the scientific literature found that out of all land management strategies geared toward reducing the effects of urbanization and sprawl, the most substantial guidance available is on how to best develop riparian buffers. Conversely, science offers very little consensus opinion to land use planners on how to determine which habitat patches to conserve and where; the amount of habitat to protect in a region or conversely the maximum amount of impervious surface to allow; the ways in which to mitigate against the negative consequences of habitat edges; or how best to design and plan for corridors. In addition, because development will continue to occur and because private lands are increasing becoming more important in species conservation, more information is needed on the level of compatibility of the various types and combinations of land uses with biodiversity. To better inform decisionmaking, the scientific community needs to provide more specific information to land use practitioners on how to implement ecologically conscious growth.

> *"Fragmentation effects are difficult to translate into management rules-of-thumb for several reasons: (1) they tend to be highly specific to the taxa, spatial scales, and ecological processes considered; (2) they vary according to the landscape type and its structure; and (3) their influence on species distribution and abundance may be obscured by local effects such as changes to certain microhabitat features (e.g., habitat degradation)."*
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> Villard (2002), Ecological Society of America, Ecological Applications 12(2), p.319

In addition, scientists should address the taxonomic bias in the literature. A recent review of 134 papers on habitat fragmentation found that over half of the research focuses on birds, the vast majority being songbirds. Mammals and plants come second, making up about 18 percent; invertebrates and reptiles/amphibians are the most understudied, with only 9 percent and 4 percent, respectively (McGarigal and Cushman 2002). Our survey found similar results. Most of the fragmentation research used for this study looks at the effects of fragmentation on bird species and, to a lesser extent, mammals. Sixty-six percent of the surveyed research on edge effects; 57 percent on patch area; 44 percent on proportion of suitable habitat; and 32 percent of the wildlife papers on buffers measured effects on bird species. Mammals made up 24 percent of the research on proportion of suitable habitat; 21 percent on patch area; 11 percent of research on buffers; and 9 percent on edge effects. Fish, invertebrate, and plant response made up anywhere from zero to 13 percent of the research. This focus has left particularly large gaps in research on reptiles and amphibians, invertebrates, and plants.

If the scientific community wishes to help curtail the loss and endangerment of species, then it will need to start addressing other taxonomic groups. The most at-risk species in the United States are flowering plants and freshwater species. In terms of species numbers, flowering plants have by far the greatest number of at-risk species (over 5,000 species are at-risk). In terms of the proportion, species that rely on freshwater habitats—mussels, crayfishes, stoneflies, amphibians, and fishes—exhibit the highest level of risk. With only 14 percent of bird species being at risk and 16 percent of mammal species, these groups are the least threatened (Master et al. 2000).

Above all else, this literature search reveals the inadequacy of the information currently available for land use planners to use in their day-to-day decisions, which have profound effects on biological diversity. The scientific community should be commended for developing theories, such as metapopulation concepts, which have important implications for applied management like endangered species recovery. However, due to the simplified assumptions implied within metapopulation models, their application to real landscapes is severely limited (Fahrig and Merriam 1994). In addition, whether metapopulations are actually common in real landscapes is largely unknown (Lindenmayer and Franklin 2002). Similarly, the SLOSS debate on whether a single large reserve is better than a group of small ones, which consumed the academic community for many years, failed to produce concrete management recommendations (Forman 1995).[29] In order for ecological principles to be put into practice, land use professionals will need general rules of thumb and specific guidelines to implement on-the-ground.

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[29] SLOSS stands for Single Large Or Several Small, which refers to whether conservation reserves are best designed as one large tract of protected land versus several smaller tracts of the equivalent area (Meffe and Carroll 1997).

Only about 10 percent of the papers reviewed in this survey provided quantitative information useful for developing conservation thresholds relevant to land use planning. Similarly, most of the papers published in the Journal of Applied Ecology during a large proportion of the last 30 years have been devoid of practical applications or management recommendations (Pienkowski and Watkinson 1996). Given the complexity surrounding habitat fragmentation, it is understandable that the scientific community is apprehensive about presenting or extrapolating research findings such that they can be easily applied to land use planning and management. Scientists even warn that providing general thresholds "may be more dangerous than useful because many species can be lost if the threshold is determined by averaging over the requirements of many species" (Mönkkönen and Reunanen 1999).

Without adequate information on land use thresholds, land use decisionmaking will continue to be uninformed by the best available science. Although reaching consensus in the scientific community on these thresholds may be an impractical goal, if enough resources are directed to answer specific land use threshold questions, research results may begin coalescing on some general range of values, which would provide useful guidance. Hopefully, this literature review will prompt scientific research that is relevant to and usable by everyday land use practitioners.

THE ROLE OF THE POLICY COMMUNITY

Although more scientific study is needed to provide ecologically-based and scientifically defensible advice on land use planning and land management thresholds, substantial research has already been conducted. The policy community could play a more active role as a conduit between the scientific community and land use planners—to help interpret the available research, help with dissemination, and communicate back to scientists on research gaps and needs. Periodical reviews of the literature, such as this survey, should be conducted to provide land use planners and land management practitioners with the most up-to-date and best available scientific information. In addition, where possible, scientific research will need to be translated into easily applied management recommendations. To ensure that land use decisions are well-informed, mechanisms should be in place to communicate current scientific understanding to the general public. Scientific institutes, such as the National Academy of Sciences, among others, should conduct or commission studies on areas where particular research gaps are found. Clear arguments, particularly those that are economically based, need to be conveyed to the land use community so that they understand why they should make land use decisions with biodiversity in mind.

THE ROLE OF THE LAND USE PLANNING COMMUNITY

The failure of land use planners to communicate their needs to the scientific community may be another reason that science inadequately addresses land use planning concerns. Land use practitioners should be encouraged to better communicate with scientists about the type of information that they need and in what format it would be most useful. An exchange about what is working on-the-ground and what is not, and about public concerns regarding land use alteration and biodiversity, would be of great benefit.

However, given the diverse habitat requirements of species and the great uncertainty and unpredictability of species and ecosystem response to habitat alteration, land use planners should not wait for the development of *the magical threshold value* before applying known general ecological guidelines, such as those presented by the Ecological Society of America's Land Use Committee. To ensure that our natural resources will be conserved for future generations, spatial planning needs to proceed immediately using the best available information.

Land use planners should err on the side of caution and adopt the most conservative threshold ranges, particularly since factors, such as global climate change, are likely to intensify land use impacts. The future change of our climate —predicted to rise globally by an average about 4° Fahrenheit (2° Celsius) by the year 2100—is likely to alter the level and timing of temperature and precipitation and to increase the frequency of environmental disturbances (like floods, droughts, hurricanes, and fires), causing shifts in suitable ecosystem and species ranges, as well as the composition of species and flows of energy and nutrients (Field et. al. 1999). For species and ecosystems to be able to withstand such drastic environmental perturbations, sufficient intact and well-connected habitat will be essential. Thus, larger patch sizes, greater habitat area, wider buffers, and more corridors are likely required under future global warming than presented in this review.

Land use planners should realize that, ultimately, there is no replacement for site-specific assessments. It is both difficult and often misleading to develop thresholds that generalize across landscapes and across ecoregions (Mönkkönen and Reunanen 1999). Since thresholds will fail to be meaningful when generalized across landscapes, ecosystems, and states, thus unable to capture the unique variation in nature, land use planners and managers need to work in close collaboration with ecologists (Mönkkönen and Reunanen 1999). Land use professionals should use the articles and research highlighted in this review only to the extent that they are appropriate for their region and to launch more in-depth analyses. This review predominately covers thresholds and guidelines for planning at a large (coarse) scale. This report, however, does not focus on the conservation of rare or localized species or habitat types, and species other than birds and mammals. It does not provide guidance on how to protect lands of greatest biological value. Rather than simply adopting the types of measures discussed in this review, land use planners should collaborate with scientists to better protect small patch communities and local-scale species and to better identify site-specific and regional conservation needs.

Although land use planners are asked to make local, site-specific decisions on a daily basis, it is still vital to maintain a landscape perspective. Numerous, small development projects that independently may not contribute to significant habitat loss, degradation, or fragmentation, may cumulatively have devastating consequences. Site-specific land use decisions would be more ecologically mindful if better informed by scientific information. Yet, to really make a difference for biodiversity, land use planners will need to begin considering their cumulative and landscape-scale impacts.

Biodiversity needs to be a central component directly considered in all land use and community planning projects. An overarching land use vision with a statewide or countywide blueprint for protecting ecosystems, representative and rare species, and broader patterns of biodiversity would serve as an important framework to guide the implementation of the specific thresholds outlined in this report. For example, Florida developed a model that identifies areas with priority conservation significance and landscape linkages (i.e., corridors) captures most of the major ecological communities and known occurrences of rare species for the entire state (Hoctor et al. 2000). Conserving regional biodiversity and accounting for land use impacts over a large scale—both spatially and temporally—will likely require inter-municipal cooperation and state-level leadership, as in the case of Florida.

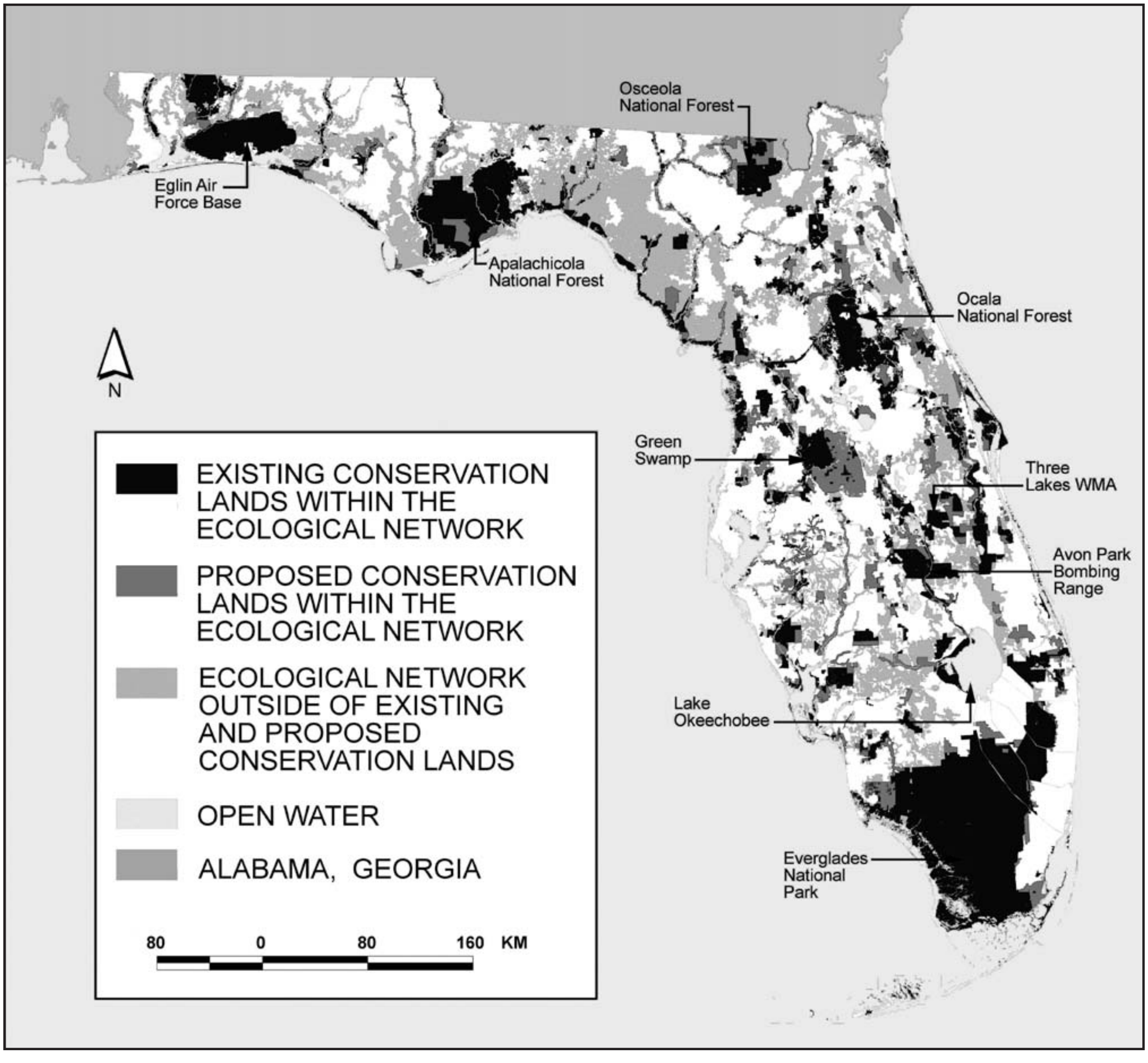

Diagram 7. Florida Ecological Network. *Results from the Florida Statewide Greenways GIS decision support model. Courtesy of the University of Florida.*

CONCLUSION

Land use decisions have profound effects on biological diversity. Land use planners, however, have many opportunities to tailor their traditional land use tools to better address biodiversity conservation. To the extent possible, planning decisions should be based on the best available science. Although the current scientific literature provides much guidance to land use planners on how to incorporate ecological knowledge into their actions, significant gaps exist in the information provided by the scientific community. The more that is known about how human mediated fragmentation impacts ecosystems, the more it is revealed that species and communities interact in complex, dynamic, and often unpredictable ways on multiple temporal and spatial scales. For science to meet the needs of local land use planners, on-going and dedicated collaboration needs to exist between the scientific, policy, and land use planning communities. Although a consensus may never develop in the scientific community on broad conservation thresholds, more effective and targeted guidance can be developed to help land use planners make more ecologically informed decisions. Without this information, little incentive exists for land use planners and land managers to factor biodiversity considerations into their decisions at all.

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APPENDIX A. FURTHER ANALYSIS

Titles and abstracts of 1,458 papers within scientific and land use planning journals were reviewed to determine whether they provide specific information on conservation thresholds that could help guide land use planning in the United States. A total of 160 papers (11 percent) were selected for inclusion in this study: 20 papers with quantitative information on minimum patch area; 27 papers on minimum proportion of suitable habitat; 25 papers on edge width distance; and 88 papers on minimum buffer width.[30]

A CLOSER LOOK AT HABITAT PATCH SIZE

Only 20 papers were found in the scientific literature to provide specific information on minimum patch area requirements pertaining to ecoregions within the United States; these papers provided 28 citations on threshold patch size.[31] The majority of papers that address habitat patch size focus primarily on estimating the area of habitat needed to sustain specific target species—as measured by species occurrence, population densities, or breeding success—and to a lesser extent species diversity or community assemblages. As reported in previous literature reviews, little is known about the amount of patch area needed to maintain essential ecosystem functions, such as primary productivity, nutrient and hydrologic cycling, or disturbance regimes (Forman 1995).

This survey reveals a taxonomic bias in scientific literature. Out of the total 28 citations, 16 citations (57 percent) pertain to birds and six citations (21 percent) to mammals. Minimum patch area requirements reported in the literature ranged from one hectare to over 2,500 hectares for birds, and from one hectare to over 220,000 hectares for mammals. Only two studies provide three relevant citations on patch size requirements for plant species: an estimated two hectares needed to sustain a representative tree community type (Elfstrom 1974), and at least 10 hectares needed to conserve an old growth forest if surrounded by secondary forest, or 100 hectares if surrounded by clearcuts (Harris 1984). Two additional studies provide patch area information for invertebrates, which indicate that habitat requirements for invertebrates may range from a minimum of 0.0004 hectares (four meters squared) up to one hectare. One study provides information for fishes, predicting a 50 percent chance of bull trout occurrence in watershed patches larger than 2,500 hectares (Rieman and McIntyre 1995).

Reported habitat patch size thresholds vary widely, even within the same taxonomic group and for the same species. This lack of convergence on minimum critical patch size reflects the large range of habitat needs exhibited by different species across different ecosystems and that species response to habitat fragmentation is very complex. This natural and inherent complexity is compounded by the lack of consistency in methodology researchers used to measure minimum habitat requirements—with differing study designs as well as parameters measured. Minimum patch area is commonly determined for target species by measuring species occurrence on a site, species densities, or nesting/breeding success. To a lesser extent studies evaluate the persistence of species diversity or community assemblages. Since different parameters are measured, different results are produced. For example, according to this survey, neotropical wood thrushes require anywhere from one hectare up to greater than 2,500 hectares of habitat depending on the variable measured (evidence of breeding versus nesting success and occurrence of nesting predation) (Robbins et al. 1989 and Trine 1998).

By in large, this review reiterates a viewpoint expressed by the scientific community several years ago: simply not enough is known about minimum critical size that should be protected in order to maintain species diversity and species composition in any given ecosystem (Lovejoy and Oren 1981 *as cited in* Saunders et al. 1991; Noss and Harris 1986). Given the lack of information on the habitat patch size requirements of species, communities, or ecosystems in the United States, land use planners should work with land and natural resource agencies and local scientists to identify the habitat patches most in need of protection.

A CLOSER LOOK AT PROPORTION OF SUITABLE HABITAT

Twenty-seven papers were encountered within the scientific literature reporting extinction or habitat fragmentation thresholds on the proportion of suitable habitat needed for an array of species. The papers surveyed provide 26 different estimates of the amount of habitat needed, depending on the species and taxa in question, and the parameter measured. The majority of findings—42 percent (11 citations)—relate to the amount of habitat recommended to maintain bird

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[30] These numbers only include papers that provided specific threshold information, which was factored into the assessment (see Appendices). Review papers and background papers are not included in these figures if they failed to provide relevant quantitative information.

[31] Because papers provide multiple findings/recommendations related to minimum patch area size requirements, the number of papers does not necessarily equal the number of citations.

species or populations. Based on this review, bird species in the United States may require anywhere from 5 percent to 80 percent of suitable remaining habitat.

The second most commonly researched group is mammals. About 23 percent of the findings (six citations) pertained to mammalian response to habitat loss and habitat isolation, which suggests that this taxonomic group may require anywhere from 6 percent to 30 percent of suitable habitat. This range, however, should not be considered representative for all mammalian groups, because it only includes small mammals (e.g., chipmunks, rabbits, squirrels) (*see* Appendix C). An important focal group—wide-ranging predators and large-bodied mammals—failed to be represented in this select review, thus, the proportions are skewed to the smaller range relevant to smaller bodied mammals.

Four studies (five citations) provide thresholds for invertebrates, ranging from 20 percent up to 60 percent of required protected habitat. Additionally, four studies base their findings on models predicting response by hypothetical species, which reveal that threshold responses may occur anywhere from as large a range as 20 percent to 90 percent of habitat loss.

As revealed by the diverse range of values offered by scientists, it is clear that no common threshold exists for the amount of habitat needed to support different populations of species or needed to minimize the negative effects of habitat fragmentation in a landscape. The lower range of proportions (e.g., 5 to 30 percent) tend to be habitat fragmentation thresholds, as determined by evidence that species are in some way negatively affected by habitat loss or habitat isolation. A significant proportion of these studies is based on predicted species response to habitat loss and fragmentation by models (at least seven of the citations). The larger proportions (e.g., 60 to 80 percent) tend to be based on models that predict the amount of habitat needed to sustain long-term species persistence or to prevent the consequences of extensive habitat fragmentation in a landscape.

Given the sparse and diverse findings, land use planners should apply these thresholds with great caution. As reported in earlier reviews, most of the habitat fragmentation studies are performed during short time periods (e.g., one or two seasons), and only provide a snap shot of how species may respond to habitat loss and isolation (Andrén 1994). In these studies, the damage to populations resulting from habitat alteration could have occurred previously (Mönkkönen and Reunanen 1999)—particularly for historically modified landscapes like eastern deciduous forests (Meier et al. 1995, Mitchell et al. 2002). Thus, the long-term consequences of fragmentation are likely not revealed in this select review because a time lag often exists between the fragmentation of a landscape and the associated response by species, populations, or systems (Andrén 1994).

CLOSER LOOK AT EDGE INFLUENCE

Twenty-five studies surveyed provide 32 findings on the distance that edges might affect habitats in the United States. Like the other conservation thresholds, the focal species of choice is birds. Sixty-six percent of the findings (21 citations within 12 articles) measure the influence of edges related to bird response, revealing that edge influence for birds extends anywhere from about 16 meters to up to almost 700 meters. Studies measuring bird or bird nest abundance report that edge effects extend between 180 and 687 meters where as those measuring predation and nesting success range from 50 to beyond 600 meters. Bird response (e.g., flushing distance) to disturbances such as roads and human traffic extends from 16.27 meters to 300 meters.

Secondarily, the influence of edges is measured by abiotic responses. Edge effects based on microclimate conditions —such as changes in light, temperature, humidity, nutrients, and moisture—are found to extend from eight meters up to 240 meters based on five studies (six citations) (Ranney et al. 1981, Laurance and Yensen 1991, Brothers and Spingarn 1992, Matlack 1993, and Chen et al. 1995).

To a lesser extent, the scientific literature provides information on the effects of edges on mammals and plants. Three studies have found that mammals avoid edge environments from at least 45 meters to 900 meters. For example, studies reveal that wide-ranging grizzly bears are displaced from 100 to 900 meters due to traffic along roadways (Mills 1996, Miller et al. 2001, and Weaver et al. 1996). One study provides evidence on the influence of edges on plant communities, finding that almost no recruitment of seedlings occurs within 65 meters of forest clear-cut edges in Oregon (Jules 1998).

Within this review, no single study is found to report edge influence in relation to invertebrate communities in the United States. As is true for the other thresholds, research has been conducted more extensively in tropical forests outside of the United States, and may serve to address knowledge gaps. For example, a study in Brazil reveals that edge effects may be more intense for invertebrate groups. Edge effects may penetrate up to 50 meters as measured by bird density; 80 meters as measured by soil moisture; 100 meters as measured by canopy height, foliage density, and leaf-litter invertebrate abundance and richness; 200 meters as measured by leaf-litter invertebrate species composition and invasion of disturbance adapted beetles; and 250 meters for invasion of disturbance-adapted butterflies (Laurance et al. 1997).

To get a better handle on the intensity of edge influence in the United States and, consequently, the amount of habitat needed to reduce the effects of edges and related disturbances, land use planners will need more site-specific guidance from ecologists. Land use planners and land managers will also need more information on effective measures that can be taken to better "soften" the many different types of edges affecting the large array of habitat types in the United States.

A CLOSER LOOK AT BUFFER WIDTH

Eighty-eight papers (156 citations) are found to provide recommendations on riparian buffer widths.[32] Of all the conservation thresholds surveyed, buffer prescriptions are the most studied and best documented. Substantial research has been conducted on the effective size of buffers, particularly related to water quality considerations, to assist regulatory and land management agencies in developing scientifically sound minimum buffer width (Castelle et al. 1994). Several literature reviews have been conducted to help inform state and local governments in developing riparian protection plans and ordinances (*see* Johnson and Ryba 1992, Furfey et al. 1997, Wenger 1999, Fischer 2000, Fischer et al. 2000, and Metro 2001). In April 2000, the U.S. Army Corp of Engineers released national recommendations for riparian buffer strip and riparian corridor design (Fischer and Fischenich 2000). This baseline research significantly informed the buffer width recommendations in this report.

One review offers the following buffer prescriptions: a three to 10 meter buffer to provide detrital input; 10 to 20 meters for stream stabilization; five to 30 meters for water quality protection; 20 to 150 meters for flood attenuation; and 30 to 500 meters or more for riparian habitat (Fischer and Fischenich 2000). The Institute's review reveals wider buffer ranges to provide a variety of functions, with a range of six to 32 meters to reduce noise and wind damage; 10 to 52 meters to stabilize stream banks; three to 80 meters to provide detrital input; four to 92 meters to remove nutrients and pollutants; three to 122 meters to remove sediments; 20 to 150 meters to provide flood attenuation; 10 to 300 meters to regulate temperature and microclimate; and three to 1600 meters to provide wildlife habitat (*see* Appendix E).

Findings in this review primarily relate to river and stream systems, however, a small number of papers explicitly address wetlands (*see* Buhlmann 1998 and Joyal et al. 2001). Although not all wetlands lie within riparian zones (e.g., isolated wetlands), they serve as vital resources and provide essential functions, such as flood storage, water purification, sediment trapping, and wildlife habitat (Mitsch and Gosselink 1993). Thus, placing buffers around these areas to protect them from nearby development activities is also advised.

Predicting the adequacy of a buffer strip to provide sufficient wildlife habitat and to protect natural species diversity is quite challenging. The width recommendations primarily focus on birds and are based on various methods—ranging from determining species presence or nesting within the area to determining species abundance, diversity, or community assemblages. Few studies attempt to measure species survival over time; thus, it is questionable whether the recommended buffers will ensure persistence of the target species and communities over the long-term.

As mentioned above, the actual effective size and adequacy of any given buffer is determined by the management target, as well as other site-specific factors, such as site and watershed conditions; intensity of adjacent land use; slope steepness; stream order; soil characteristics (depth, texture, erodibility, moisture, pH); floodplain size and frequency of inundation; hydrology; buffer characteristics (e.g., type, density, and structure of vegetation, and buffer length); and landowner/manager objectives (Naiman et al. 1993, Castelle et al. 1994, Wenger 1999, Todd 2000). For example, larger buffers may be necessary when the buffer strip is in poor condition (e.g., comprised of sparse exotic vegetation, disturbed/erodible soils); is located on steep bank slopes (e.g., greater than 10 percent to 15 percent);[33] is surrounded by intense land uses; or is located within watersheds with increased impervious surfaces that results in high nutrient, chemical, and sediment inputs, and runoff (e.g., adjacent to urban/suburban areas or intensive agricultural farmland). Such factors should be considered when evaluating the applicability of the general recommended buffer sizes (*see* Wenger 1999, Fischer and Fischenich 2000, Metro 2001). In addition, management decisions should not only be based on site-specific characteristics but also on basin or watershed level needs to maintain the hydrologic connectivity and natural variability of these systems (Naiman et al. 1993, Pringle 2001). [34]

A CLOSER LOOK AT CORRIDORS

To determine whether or not corridors are effectively enhancing species conservation, scientists evaluate whether (and how) patch occupancy, species abundance and diversity, colonization, and immigration rates change with and without the presence of corridors (Beier and Noss 1998).

Many studies lend support to the premise that corridors retain important species or provide faunal habitat (Bennett 1998). Few studies, however, provide clear evidence that corridors are required for species movement in landscapes (Hobbs 1992). Many species simply do not respond or require corridors (Rosenburg et al. 1997, Bowne et al. 1999, Hannon and Schmiegelow 2002). For example, male-hooded warblers preferentially travel across open areas, even in

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[32] Some papers recommend multiple buffer widths, for example, they may suggest different widths for different species or functions of concern. Thus, the number of papers does not equal the number of citations.

[33] Herson-Jones et al. 1995 (found that greater than 10 percent slopes are steep slopes) and Nieswand et al. 1990 (found that greater than 15 percent slopes are steep) (as cited in Wenger 1999).

[34] Hydrologic connectivity refers to water-mediated transfer of matter, energy, or organisms within or between elements of the hydrologic cycle (Pringle 2001).

landscapes with corridors connecting habitat patches (Norris and Stutchbury 2001). For species like the Northern spotted owl, which has been found to disperse randomly, the presence of corridors will likely not enhance its survival (Murphy and Noon 1992 *as cited in* Lindenmayer and Franklin 2002). Because of the complexity of animal behavior, land use planners should not assume that establishing corridors between habitat patches in a region will automatically guarantee enhanced and effective dispersal and recolonization among the separated wildlife populations.

The benefits of corridors should be weighed against their potential repercussions. Scientists warn that corridors may potentially transmit diseases, fires, or other catastrophes among habitats and populations, as well as increase invasions by non-native invasions or exposure to predation (Simberloff and Cox 1987, Noss 1991, Noss and Cooperrider 1994). To add to the complexity of this issue, many corridor studies—both those that claim corridor benefits and those that claim costs—suffer from design flaws that limit their ability to discern the real conservation value of corridors (Beier and Noss 1998).

A recent scientific review is able to shed some light on the corridor controversy; a review by Beier and Noss (1998) presents evidence from well-designed studies that suggest that corridors seem to be providing sufficient connectivity to enhance the viability of wildlife populations. Conversely, a lack of evidence backs the assertion that the presence of corridors actually has a greater adverse impact than their absence (Beier and Noss 1998, Hobbs 1992). Although wildlife corridors should not be automatically assumed to be an essential component of all land conservation strategies (Lindenmayer and Franklin 2002), planners should consider corridors as one potentially valuable conservation tool (Beier and Noss 1998, Hobbs 1992).

APPENDIX B. MINIMUM PATCH AREA

Minimum patch area requirements (in hectares) found within the scientific literature (as of December 2001) to maintain populations or communities of animal or plant species in the United States. One hectare is about 2.5 acres.

TAXA	PATCH AREA	FINDING	STATE	CITATION
Birds				
	≥ 1 ha	Minimum area requirement for breeding wood thrushes is 1 ha, although nesting success on fragments of that size would be extremely low.	MD, PA, VA, WV	Robbins et al. 1989
	> 1	Five species of chaparral-requiring birds were supported by census plots larger than 1 ha.	CA	Soulé et al. 1992
	≥ 2 ha (seed-eating birds) ≥ 40 ha (insect-eating birds)	The minimum area point[1] for insect-eating birds was estimated to be at least 40 ha, in contrast to 2 ha for seed-eating birds. This is interpreted as the habitat size needed to support a representative bird community.	NJ	Forman et al. 1976[2] Galli et al. 1976[2]
	≥ 5 ha (marsh)	Ten of the 25 species did not occur in marshes less than 5 ha.	IA	Brown and Dinsmore 1986
	≥ 5, ≥ 30, ≥ 40, ≥ 50, ≥ 55 ha	Estimates of minimal area requirements for five area-sensitive species ranged from 5 to 55 ha.	IL	Herkert 1994
	≥ 6.5 ha, 15.4 -32.6 ha	Black tern required 6.5 ha in heterogeneous landscapes, but required 15.4 - 32.6 ha in homogeneous landscapes.	SD	Naugle et al. 1999
	≥ 10 ha (forest)	Forest patches ≥ 10 ha had much greater bird diversity than patches < 3.25 ha	GA	McIntyre 1995
	> 80 ha	In fragments < 80 ha, nesting success was low (43%), and nest predation was high (56%).	PA	Hoover et al. 1995
	< 20 ha, >2500 ha	Based on a study of cowbird parasitism and nest predation on 3 large forest tracts (1100 - 2200 ha) in southern Illinois, maintaining wood thrush populations in the midwest might require > 2500 ha reserves. In the east even a small woodlot (< 20ha) may sustain a population.	IL	Trine 1998
Mammals				
	> 1 ha	Control plots larger than 1 ha supported most species of rodents.	CA	Soulé et al. 1992
	≥ 5 ha	Cottontails may become vulnerable to extinction if large patches ≥ 5.0 ha are not maintained.	NH	Barbour and Litvaitis 1993
	≥ 10 ha	Fragments < 10 ha did not support populations of native rodents.	CA	Bolger et al. 1997

TAXA	PATCH AREA	FINDING	STATE	CITATION
	≥ 900 ha (9 km2)	More than 80% of bear sitings occurred in blocks of undisturbed habitat ≥ 9 km^2.	MT	Mace et al. 1996[3]
	≥ 2800 ha (28 km2)	Grizzly bears in the Yellowstone ecosystem should have security blocks 28 km^2 in size.	MT, ID, WY	Mattson 1990[3]
	≥ 220,000 ha (2200 km2)	Model predicts low extinction risk for cougars in areas as small as 2200 km^2, but w/ increasing risk with little immigration.	CA	Beier 1993
Fishes				
	> 2500	Found support that suitable patch size (as defined by watersheds above 1600 m elevation) influences the occurrence of bull trout. Predicted probability of occurrence is 0.5 for patches larger than 2500 ha.	ID	Rieman and McIntyre 1995
Invertebrates				
	≥ .0004 ha (4m2)	Vegetation patches ≥ 4m^2, as well as open areas, were important to the distribution and abundance of carabid beetles.	OH	Crist and Ahern 1999
	≥ 1 ha	Observed minimum patch size for occupancy by populations of 3 butterfly species is 1 ha.	model	Hanski 1994
Plants				
	≥ 2 ha (5 acres)	Minimum area point[1] for tree communities was estimated to be about 2 ha.	NJ	Elfstrom 1974[2]
	≥ 10, ≥ 100 ha	Conserving an old-growth forest might require 10 ha if surrounded by comparable forest, but 100 ha if surrounded by a clearcut.	—	Harris 1984[4]

— Indicates that the geographic location was not determined because the recommendation was cited secondarily from another review article.

model indicates that the research was conducted through modeling and therefore is not specific to any geographic area.

[1] Minimum area point is the point on a species-area curve, which shows the relationship between species number and habitat area, where there is an abrupt change in the slope. The minimum area point has been considered an index of how large a community must be to representative of the community type (Forman 1995).

[2] *As cited in* Forman 1995

[3] *As cited in* Weaver et al. 1996

[4] *As cited in* Franklin 1993

APPENDIX C. PROPORTION OF SUITABLE HABITAT

Recommended minimum proportions of suitable habitat found within the scientific literature (as of December 2001) to maintain long-term persistence of viable populations or communities of species or to minimize the negative consequences of habitat fragmentation in the United States.

TAXA	PROPORTION OF SUITABLE HABITAT	FINDING	STATE	CITATION
Birds				
	≥ 5%	When < 5% of area was covered by habitat, there was an effect on bird density.	WI	Ambuel and Temple 1983[1]
	≥ 5%	When < 5% of area was covered by habitat, there was an effect on bird community.	—	Howe 1984[1]
	> 8%	When 8% of area was covered by habitat, there was an effect on land bird community.	—	Nilsson 1978[1] Nilsson 1986[1]
	≥ 10%	When < 10% of area was covered by habitat, there was an effect on species richness.	—	Soulé et al. 1988[1] Bolger et al. 1991[1]
	>10-30%	The negative effects of patch size and isolation on native species may not occur until the landscape consists of only 10-30% of the original habitat.	review	Andrén 1994
	> 15%	When 15% of area was covered by habitat, there was an effect on bird density.	—	Askins et al. 1987[1]
	> 20%	When 20% of area was covered by habitat, there was an effect on bird community.	MD	Lynch and Whigham 1984[1]
	> 22%	When 22% of area was covered by habitat, there was an effect on land bird community	—	Whitcomb et al. 1981[1]
	> 50%	Numerous species were more likely to inhabit wetlands in landscapes where less than 50% of the upland matrix was tilled.	SD	Naugle et al. 2001
	≥ 60%	A model assuming 60% suitable habitat suggests a high likelihood for the longterm persistence of Northern spotted owls.	model	Lamberson et al. 1994
	> 80%	Metapopulation model predicted that the Northern spotted owl population would go extinct if the proportion of old-growth forest was reduced to less than 20% of landscape.	model	Lande 1988[4] Lamberson et al. 1992[4]
Mammals				
	> 6%	When 6% of area was covered by habitat, there was an effect on chipmunk density.	—	Henderson et al. 1985[1]
	> 6%	When 6% of area was covered by habitat, there was an effect on pika abundance.	—	Smith 1974[1] Smith 1980[1]
	≥ 10%	When < 10% of area was covered by habitat, there was an effect on mammal species richness.	—	Soulé et al. 1992[1]
	> 10%	When 10% of area was covered by habitat, there was an effect on Columbian ground squirrel presence/absence.	—	Weddell 1991[1]
	> 10-30%	The negative effects of patch size and isolation on the native species may not occur until the landscape consists of only 10–30% of the original habitat.	review	Andrén 1994
	> 15%	When 15% of area was covered by habitat, there was an effect on small mammal presence.	—	Lomolino et al. 1989[1]

TAXA	PROPORTION OF SUITABLE HABITAT	FINDING	STATE	CITATION
Invertebrates				
	≥ 20%	The threshold for changes in movement patterns of beetles occurred at 20% coverage of cells.	CO	Wiens et al. 1997
	≥ 20%	Clover patches became significantly more isolated below 20% habitat, which disrupted the predator foraging behavior of ladybird beetles, decreasing their ability to serve as biocontrol agents of aphids.	model	With et al. 2002
	≥ 40%	Habitat specialists of grasshoppers exhibited limited movement and disjunct populations—which can affect population persistence—when preferred habitat occupied less than 40% of the landscape.	model	With and Crist 1995
	≥ 40, ≥ 60%	Rare species were disproportionately affected by fragmentation and did not occur in patches with less than 40% habitat. Over half of the species were never observed in plots with less than 60% habitat remaining.	OH	Summerville and Crist 2001
Hypothetical Species				
	> 10-30%	As habitat loss continues beyond the threshold (occurring somewhere in the range of 70-90% habitat loss) decline in population performance should become much more severe. But model predicts that habitat fragmentation begins to occur when about 60% of original vegetation remains.	model	Gardner et al. 1987[2]
	≥ 20%	The threshold value of habitat amount is 20% habitat, below which the effects of habitat fragmentation on population persistence may become evident.	—	Andrén 1994[3] Fahrig 1998[3]
	> 70%	Models of forest landscapes forecast that patches of old-growth forest can become fragmented even when about 70% of the landscape cover remains.	model	Franklin and Forman 1987
	> 80%	Terrestrial species with low demographic potential could not persist in landscape even with 80% of suitable habitat in landscape.	model	Lande 1987[4]

— Indicates that the geographic location was not determined because the recommendation was cited secondarily from another review article.
model indicates that the research was conducted through modeling and therefore is not specific to any geographic area.
review indicates papers that base recommendation on a survey of the literature.

[1] *As cited in* Andrén 1994

[2] *As cited in* Dooley and Bowers 1998

[3] *As cited in* Fahrig 2001

[4] *As cited in* With and Crist 1995

APPENDIX D. EDGE INFLUENCE

Distances (in meters) that edge effects penetrate into habitats in the United States as found within the scientific literature (as of December 2001), according to abiotic, bird, mammal, and plant response.

TAXA/SUBJECT	EDGE INFLUENCE	FINDING	STATE	CITATION
Abiotic				
	8 m	Microclimatic differences ceased to exist beyond 8 m into forest fragments.	IN	Brothers and Spingarn 1992
	13.3 m	Model indicated that elevated soil temperatures may extend up to 13.3 m from edge.	model	Laurance and Yensen 1991
	≥ 15 m	In deciduous forest patches, microclimate changes were estimated to extend at least 15 m from the forest edge to the interior.	WI	Ranney et al. 1981[2]
	50 m	Significant edge effects were detected in light, temperature, litter moisture, vapor pressure deficit, humidity, and shrub cover, affecting the forest microenvironment up to 50 m from the edge.	PA, DE	Matlack 1993
	15-60 m (solar radiation) > 240 m (humidity and wind speed)	Solar radiation gradients extend 15–60 m into upland old-growth forest and humidity and wind speed gradients at > 240 m.	—	Chen et al. 1995[9]
Birds				
	16.27 m, 16.95 m, 37.73 m	Maximum flushing* distance in response to pedestrians and dogs was 16.27 m (American robin), 16.95 m (vesper sparrow), and 37.73 m (western meadowlark).	CO	Miller et al. 2001
	50 m	Predation and parasitism rates are often significantly greater within 50 m of an edge.	—	Paton 1994[3]
	50 m	Murrelet nest success was higher when nests were more than 50 m from the forest edge.	—	Nelson and Hamer 1995[4]
	75 m	Estimated that edge-related nest predation extended 75 m into forested buffer strip.	ME	Vander Haegen and Degraaf 1996
	75 m, 100 m	For the majority of species found to have reduced numbers near trails due to nest predation and brood parasitism by brown-headed cowbirds, the zone of influence of trails appears to be around 75 m; however, Townsend's Solitaires exhibited reduced numbers as far as 100 m away from trail.	CO	Miller et al. 1998
	75 m, 125 m, 140 m, 160 m, 210 m, 300 m	Buffer zones that would prevent flushing by approximately 90% of the wintering individuals of a species are: American kestrel, 75 m; merlin, 125 m; prairie falcon, 160 m; rough-legged hawk, 210 m; ferruginous hawk, 140 m; and golden eagle, 300 m.	CO	Holmes et al. 1993
	100 m	Flushing distances of waterbirds in response to pedestrians, all-terrain vehicles, automobiles, and boats, indicate that human disturbance extends up to 100 m.	FL	Rodgers and Smith 1997

TAXA/SUBJECT	EDGE INFLUENCE	FINDING	STATE	CITATION
	180 m	Avian densities were altered up to 180 m away from homes on the perimeter of ex-urban developments.	CO	Odell and Knight 2001
	200–500 m	The abundance of interior habitat bird species was reduced within 200 to 500 m of an edge.	CA	Bolger et al. 1997b[1]
	≥ 300 m	Nest parasitism by brown-headed cowbirds decreased with distance away from forest edge but extended ≥ 300 m into the forest.	—	Brittingham and Temple 1983[5]
	511 m, 687 m	Most Cooper hawk nests occurred 511 m from paved roads and 687 m from human habitation.	Northeast	Bosakowski et al. 1992
	600 m	Effect of increased predation extends 600 m into habitat.	—	Wilcove et al. 1986[1]
Mammals				
	≥ 45 m	The influence of a clearcut on small mammals (California red-backed vole and deer mouse) extends at least 45 m into the forest from its edge.	—	Mills 1996[6]
	81.92 m	Maximum flushing distance of mule deer in response to pedestrians and dogs was 81.92 meters.	CO	Miller et al. 2001
	100–900 m	Human traffic along open roads displaces most grizzly bears from 100–900 meters.	—	Mattson et al. 1987[7] McLellan and Shackleton 1988[7] Aune and Kasworm 1989[7] Kasworm and Manley 1990[7] Mace et al. 1996[7]
Plants				
	65 m	Populations in forest remnants within 65 m of forest clear-cut edges have almost no recruitment of young plants.	OR	Jules 1998
General				
	5000 m	In different habitats and for different taxa, edge effects may penetrate up to 5 km.	—	Janzen, 1986[8]

* Flushing distance is the distance that an animal may flee in response to a disturbance, such as in response to pedestrian or pets on a trail or vehicular traffic on roads.
— Indicates that the geographic location was not determined because the recommendation was cited secondarily from another review article.
model indicates that the research was conducted through modeling and therefore is not specific to any geographic area.

[1] *As cited in* Metro 2001.

[2] *As cited in* Collinge 1996

[3] *As cited in* Hartley and Hunter 1998

[4] *As cited in* Meyer and Miller 2002

[5] *As cited in* Robbins et al. 1989

[6] *As cited in* Lidicker 1999

[7] *As cited in* Weaver et al. 1996

[8] *As cited in* Laurance and Yensen 1991

[9] *As cited in* Brosofske et al. 1997

APPENDIX E. RIPARIAN BUFFER WIDTH

Recommended minimum riparian and wetland buffer widths (in meters) to maintain water quality and wildlife functions within ecoregions of the United States, as found within the scientific literature (as of December 2001).

FUNCTION	TAXA/SUBJECT	BUFFER WIDTH	CITATION
Miscellaneous			
	Noise	≥ 6 m (mature evergreen)	Harris 1985[3]
	Wind damage prevention	≥ 23 m	Pollock and Kennard 1998[3]
	Noise	≥ 32 m (heavily forested)	Groffman et al. 1990[5]
Detrital Input			
	Organic litterfall	1/2 SPTH	FEMAT 1993[3]
	Large Woody Debris	1 SPTH	FEMAT 1993[3]
	Large Woody Debris	1 SPTH	Spence et al. 1996[3]
	Woody Debris	3–10 m	Fischer and Fischenich 2000
	Woody Debris	10–30 m	Wenger 1999
	Organic litterfall	≥ 30 m	Erman et al. 1977[3]
	Woody Debris	≥ 30 m (forested watersheds)	Pollock and Kennard 1998[3]
	Woody Debris	≥ 31 m	Bottom et al. 1983[4]
	Woody Debris	≥ 46 m	McDade et al. 1990[3]
	Organic litterfall	≥ 52 m	Spence et al. 1996[3]
	Woody Debris	≥ 80 m	May 2000[3]
Temperature and micro-climate regulation			
	Microclimate	3 SPTH	FEMAT 1993[3]
	Shade	10–30 m	Osborne and Kovacic 1993[3]
	Temperature control	10–30 m	Wenger 1999
	Water temperature	10–30 m	Castelle et al. 1994
	Shade	11–24 m	Brazier and Brown 1973[5]
	Water temperature	≥ 12 m	Corbett and Lynch 1985[4]
	Water temperature	15–30 m	Hewlett and Fortson 1982[4]
	Shade	23–38 m	Steinblums et al. 1984[5]
	Shade	≥ 30 m	Spence et al. 1996[3]
	Shade	≥ 30 m	FEMAT 1993[3]
	Shade	≥ 30 m	May 2000[3]
	Maintenance of water temperature within 1°C of former mean	≥ 30 m	Lynch, Corbett, and Mussalem 1985[1]
	Water temperature	30–43 m	Jones et al. 1988[4]
	Air temperature, solar radiation, wind, humidity	≥ 45–300 m	Brosofske et al. 1997
	Microclimate regulation	≥ 100 m	May 2000[3]
	Microclimate regulation	61–160 m	Knutson and Naef 1997[3]
Bank Stabilization			
	Bank Stabilization	1/2 SPTH	FEMAT 1993[3]
	Bank Stabilization	10–20 m	Fischer and Fischenich 2000

FUNCTION	TAXA/SUBJECT	BUFFER WIDTH	CITATION
	Stream/channel stabilization	20–30 m	Corbett and Lynch 1985[4]
	Stream stabilization/sediment control	≥ 38 m	Cederholm 1994[3]
	Bank Stabilization	≥ 52 m	Spence et al. 1996[3]
Flood Attenuation			
	Floodplain storage	20–150 m	Fischer and Fischenich 2000
Sediment Removal			
	Sediment removal	≥ 3m (sand), ≥ 15 m (silt), ≥ 122m (clay)	Wilson 1967[5]
	Sediment removal	5–30 m	Fischer and Fischenich 2000
	Sediment removal	8–46 m (depending on slope)	SCS 1982[4]
	Sediment (85% removal)	≥ 9 m (grass filter strips, 7%, 12% slopes)	Ghaffarzadeh et al. 1992[4]
	Suspended solids (84% removal)	≥ 9 m (vegetated filter strip)	Dillaha et al. 1989[1]
	Sediment removal	9–30 m	Wenger 1999
	Sediment removal	10–60 m	Castelle et al. 1994
	Sediment removal	≥ 15 m	Budd et al. 1987[4]
	Sediment removal	≥ 15.6 m	Broderson 1973[4]
	Sediment removal	≥ 23 m	Schellinger and Clausen 1992[4]
	Suspended sediment (92% removal)	≥ 24.4 m (vegetated buffer)	Young et al. 1980[4]
	Sediment removal	≥ 25 m	Desbonnet et al. 1994[4]
	Sediment removal	≥ 30 m	Erman et al. 1977[3]
	Sediment removal	≥ 30m	Moring 1982[3]
	Sediment removal	≥ 30 m	May 2000[3]
	Sediment (75% removal)	30–38 m	Karr and Scholosser 1977[4]
	Sediment (75–80% removal)	≥ 30 m	Lynch, Corbett, and Mussalem 1985[1]
	Sediment (80% removal)	≥ 61 m (grass filter strip and vegeated buffers)	Horner and Mar 1982[1]
	Sediment (50% removal)	≥ 88 m	Gilliam 1988[4]
Nutrient/Pollutant Removal			
	Nitrogen, Phosphorus, Potassium, and Fecal Bacteria	≥ 4 m (grass filter strip and forested buffers)	Doyle et al. 1997[1]
	Nitrates and Phosphates (90% removal)	≥ 5 (grass filter strip)	Madison et al. 1992[1]
	Nutrient removal	5–30 m	Fischer and Fischenich 2000
	Nitrates (almost complete removal)	≥ 7 m	Lowrance 1992[1]
	Removal of Phosphorus (79%) and Nitrogen (73%)	≥ 9 m (vegetated filter strip)	Dillaha et al. 1989[1]
	Nitrogen and Phosphorus	≥ 10 m	Corley et al 1999[1]
	Nutrient and Metal	≥ 10 m	Petersen et al. 1992[4]
	Nutrient removal	10—90 m	Castelle et al. 1994
	Nitrate Concentrations	15–30 m	Wenger 1999

FUNCTION	TAXA/SUBJECT	BUFFER WIDTH	CITATION
	Nutrient and metal	≥ 15 m	Castelle et al. 1992[4]
	Phosphorus	≥ 15 m (hardwood buffer)	Woodard and Rock 1995[1]
	Nutrient and metal	≥ 16 m	Jacobs and Gilliam 1985[4]
	Estradiol (98% decrease)	≥ 18 m (grass filter strip)	Nichols et al. 1998[1]
	Nitrogen and Phosphorus (80 and 89% removal, respectively)	≥ 19 m (riparian forest buffer)	Shisler, Jordan, and Wargo 1987[1]
	Nitrates (up to 100%)	20–30 m	Fennessy and Cronk 1997[3]
	Fecal coliform reduction	23–92 m	SCS 1982[5]
	Pollutant removal	≥ 30 m	May 2000[3]
	Fecal coliform reduction	≥ 30 m	Grismer 1981[5]
	Nutrient reduction to acceptable levals	≥ 30 m	Lynch, Corbett, and Mussalem 1985[1]
	Nutrient and metal removal	30–43 m	Jones et al. 1988[5]
	Nutrient and metal removal	≥ 36 m	Young et al. 1980[4]
Wildlife and Plant Species			
	General wildlife	3–183 m	FEMAT 1993[3]
	General wildlife habitat	≥ 10 m	Petersen et al. 1992[5]
	General species diversity	10–100 m	Castelle et al. 1994
	General bird habitat	≥ 15 m	Milligan 1985[5]
	Fish (Cutthroat trout, rainbow trout, and steelhead)	15–61 m	Knutson and Naef 1997[3]
	Birds	≥ 15–200 m	Stauffer and Best 1980
	Aquatic wildlife habitat	20–150 m	Fischer and Fischenich 2000
	General wildlife habitat	≥ 23 m	Mudd 1975[5]
	General wildlife habitat	≥ 27 m	WDOE 1981[5]
	Invertebrates (aquatic insects)	≥ 30 m	Erman et al. 1977[3]
	Invertebrates (macroinvertebrate diversity)	≥ 30 m	Gregory et al. 1987[3]
	Fish (cutthroat trout)	≥ 30 m	Hickman and Raleigh 1982[3]
	Invertebrates (benthic communities)	≥ 30 m	Newbold et al. 1980[5]
	Amphibians (frogs and salamanders)	≥ 30 m (riparian forest buffer)	NRCS 1995[3]
	Fish (brook trout)	≥ 30 m	Raleigh 1982[5]
	Fish (rainbow trout)	≥ 30 m	Raleigh et al. 1984[3]
	Fish (chinook salmon)	≥ 30 m	Raleigh et al. 1986[5]
	Invertebrates (benthic communities)	≥ 30 m	Roby et al. 1977[5]
	Amphibians, Reptiles, Vertebrates	≥ 30 m (riparian forest buffer)	Rudolph and Dickson 1990[1]
	Fish (salmonid egg development)	≥ 30 m	Spackman and Hughes 1995[1]
	Plants (vascular plant diversity)	≥ 30 m	Spackman and Hughes 1995[1]
	Fish (fish diversity and densities)	≥ 30 m	Stewart et al. 2000
	Mammals (beavers)	30–100 m	Jenkins 1980[9]
	General wildlife habitat	≥ 32 m	Groffman et al. 1990[5]
	Birds (Willow flycatcher nesting)	≥ 37.5 m	Knutson and Naef 1997[3]

FUNCTION	TAXA/SUBJECT	BUFFER WIDTH	CITATION
	Birds (diversity and assemblages)	≥ 40 m	Hagar 1999
	Birds (assemblages and persistence)	≥ 45 m	Pearson and Manuwal 2001
	Mammal (gray squirrel)	≥ 50 m	Dickson 1989[1]
	Birds (neotropical migrants, interior species)	≥ 50 m	Tassone 1981[3]
	Birds (raptors)	50–1600 m	Richardson and Miller 1997[7]
	Fish (trout, salmon)	≥ 61 m	Castelle et al. 1992[3]
	Mammals (deer)	≥ 61 m	NRCS 1995[3]
	General wildlife	≥ 61 m	Zeigler 1988[5]
	Mammals (small)	67–93 m	Jones et al. 1988[5]
	Reptiles (gravid mud turtles, Florida cooters, slider turtles)	≥ 73 m (90% protection)	Burke and Gibbons 1995
	Birds	75–200 m	Jones et al. 1988[3]
	Mammal (beaver)	≥ 91 m	NRCS 1995[3]
	Mammals (large)	≥ 100 m	Jones et al. 1988[5]
	Birds (neotropical migrants)	≥ 100 m	Fischer 2000
	Wildlife habitat	≥ 100 m	Fischer, Martin, and Fischenich 2000; and Fischer and Fischenich 2000
	Birds (yellow-billed cuckoo breeding habitat)	≥ 100 m	Gaines 1974[2]
	Birds (neotropical migrant diversity and functional assemblages)	≥ 100 m	Hodges and Krementz 1996
	Birds (forest bird nesting habitat)	≥ 100 m	Keller et al. 1993
	Reptiles (Western pond turtle nesting habitat)	≥ 100 m (stream buffer)	Knutson and Naef 1997[3]
	Aquatic wildlife	≥ 100 m	May 2000[3]
	Birds (red-shouldered hawk and forest bird breeding habitat)	≥ 100 m	Mitchell 1996[2]
	Birds (pileated woodpecker nesting habitat)	≥ 100 m	Small 1982[3]
	Birds (neotropical migrant abundance)	≥ 100 m	Triquet, McPeek, and McComb 1990[2]
	Terrestrial riparian wildlife communities	100–300 m (300 m for forest interior species)	Wenger 1999
	Reptiles (spotted turtles nesting habitat)	120 m (wetland buffer)	Joyal et al. 2001
	Reptiles (turtles)	≥ 135 m (wetland buffer)	Buhlmann 1998[1]
	Birds (Pileated woodpecker)	≥ 137 m	Castelle et al. 1992[3]
	Birds (species diversity)	≥ 150 m	Spackman and Hughes 1995[2]
	Birds (reduce edge-related nest predation)	≥ 150 m	Vander Haegen and DeGraaf 1996
	Amphibians (salamanders)	≥ 165 m	Semlitsch 1998
	Birds (Bald eagle, nesting ducks, herons, sandhill cranes)	≥ 183 m	Knutson and Naef 1997[3]
	Mammals (fawning of mule deer)	≥ 183 m	Knutson and Naef 1997[3]

FUNCTION	TAXA/SUBJECT	BUFFER WIDTH	CITATION
	Plants (minimize non-native vegetation)	≥ 198 m	Hennings 2001[3]
	Birds (Rufous-sided towhee)	≥ 200 m	Knutson and Naef 1997[3]
	Reptiles (Blanding's turtles nesting habitat	≥ 410 m (wetland buffer)	Joyal et al. 2001
	Reptiles (False map turtles, slider turtles, lotic turtles dispersal)	≥ 449 m	Bodie and Semlitsch 2000
	Birds (complete assemblages)	≥ 500 m	Kilgo et al. 1998[1]
General Protection of Aquatic Systems			
	Multiple functions	1–90 m	Todd 2000
	Multiple functions	≥ 10 m	Fischer and Fischenich 2000
	Multiple functions	≥ 15 m	Fischer, Martin, and Fischenich 2000
	Multiple functions	30 m	Furfey et al. 1997
	Sediment/contaminant control, general water quality maintenance	30.5 m (+0.61 m per 1% slope)	Wenger 1999
	Wetland and river integrity	≥ 335 m	Schaefer et al. 1991[6]

SPTH, or site potential tree height, is used as a standard measurement to allow for multiple riparian functions. SPTH is measured in various ways. FEMAT (1993) defines SPTH the height of a site potential tree as the average maximum height of the tallest dominant trees of 200 years or more of age for a given site class (*For further discussion, refer to Metro 2001*).

[1] *As cited in* Fischer and Fischenich 2000.

[2] *As cited in* Fischer 2000.

[3] *As cited in* Metro 2001.

[4] *As cited in* Furfey et al. 1997

[5] *As cited in* Johnson and Ryba 1992

[6] *As cited in* Burke and Gibbons 1995

[7] *As cited in* Fischer, Martin, and Fischenich 2000

[8] *As cited in* Hagar 1999

[9] *As cited in* Allen 1983

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