ISSUES IN DEFINING, DETECTING, AND QUANTIFYING RARE SPECIES

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TABLE OF CONTENTS

INTRODUCTION

NATIVE FISHES IN THE SOUTHWEST: STATUS AND TRENDS

Complex geologic, climatic, and evolutionary processes that started more than 100 million of years ago resulted in a variety of desert fishes well adapted to extreme conditions of heat and water fluctuations during alternating periods of flood and drought. About 170 species comprise the unique and ancient assemblage of western United States native fishes (Downling and Childs 1992). Comparing ichthyofaunas east and west of the Rocky Mountain axis, western fish fauna is characterized as depauperate and presenting a high number of endemic subfaunas, as a result of a long history of disruptive geologic and climatic events that substantially reduced the diversity, availability, and reliability of aquatic habitats (Minckley and Douglas 1991). In addition to these factors, detrimental human activities on aquatic systems -including habitat destruction and modification, and introduction of non-native species- have contributed to the rapid and drastic decline of desert fishes in the Southwest to the point that most of them are now listed as threatened or endangered (Miller 1961, Deacon et al. 1979, Ono et al. 1983, Minckley and Deacon 1968, 1991, Minckley 1973, 1985, 1991, Minckley and Brooks 1985, Williams et al. 1985, 1989, Moyle and Barton 1986, Minckley and Douglas 1991, Douglas et al. 1994). Similar declines have been observed in many parts of the world (Miller 1961, Hendrickson 1983, Edwards and Contreras-Balderas 1991, Contreras-Balderas 1991, Crivelli 1995, Collares-Pereira et al. 1999, Goren and Ortal 1999, Fuller et al. 1999).

Aquatic ecosystems in the world have been invaded successfully by both exotic plants and animals. Some of these invasions have been spectacular and have occasioned considerable concern because of the profound economic and cultural consequences (Vermeij 1996). An important management measure in controlling invading species would be their early detection in the ecosystem. The present work develops on the idea that both endangered natives and recently introduced non-natives might be studied under the framework of rarity.

SPECIFIC THREATS TO NATIVE FISH: THE CENTRAL ARIZONA PROJECT

In Arizona, a portion of the Colorado River water is now deviated through a series of pipelines and aqueducts that begin in Lake Havasu and cross the central and southern portions of the state to end at an area near Tucson. This important project is called the Central Arizona Project (CAP), completed in 1993 largely by the U.S. Bureau of Reclamation (BOR). In the last decade, the CAP has been the subject of debate as a potential corridor leading to transport of non-native fishes and other aquatic organisms from the Colorado River to central and southern Arizona. After its completion, the Fish and Wildlife Service (FWS) issued a Biological Opinion (BO) on transportation and delivery of CAP water to the Gila River Basin and determined that the project would jeopardize continued existence of four threatened or endangered fishes: Gila topminnow (*Poeciliopsis occidentalis*), spikedace (*Meda fulgida*), loach minnow (*Tiroga cobitis*), and razorback sucker (*Xyrauchen texanus*). One alternative in the BO directed the BOR to develop a monitoring plan for implementation in conjunction with FWS and Arizona Game and Fish

Department (AGFD). BOR was also directed to determine baseline fish community composition and distribution and to monitor impact of non-native fishes on existing fish communities in selected waters of the Gila River Basin.

Several species of fish detected in the CAP canals have not been detected during monitoring efforts on the Gila or San Pedro rivers since 1995 (Table 1). Any impact of these fishes, as well as other organisms not currently found on the two rivers, may manifest itself by changing the abundance of fishes (native and non-native) that occur on the San Pedro and Gila Rivers. Fish that are currently common and/or widespread on the rivers can be monitored using conventional techniques; however; rare species present difficulties in merely determining whether they are present, let alone in determining their actual density.

Four species on the Gila and San Pedro River are listed: Gila topminnow, spikedace, loach minnow, and razorback sucker. None of these four species has been detected during AGFD surveys in 1995 through 1998. Depending on how rarity is defined, Table 2 can be used to broadly identify species that are restricted spatially (black bullhead, threadfin shad, bluegill, smallmouth bass, black crappie, and flathead catfish) and/or occur at low densities where they are found (black bullhead, threadfin shad, green sunfish, bluegill, smallmouth bass, largemouth bass, fathead minnow, black crappie, and flathead catfish) on the San Pedro and Gila Rivers.

In addition to following any changes in density of current fish species, BOR wants to track any invasion by the non-native species currently found in the canals but not the Gila or San Pedro Rivers (Table 1). Agencies monitoring for such an invasion wish to be able to detect the fishes at the low densities.

Table 1. Species detected since 1970 in target canals or the Salt River, now with connections via the CAP to the San Pedro and Gila Rivers, where these species have not been detected in AGFD monitoring. Taken from Clarkson (1999).

Common name	Scientific name
Oscar	*Astronotus ocellatus*
Goldfish	*Carassius auratus*
Grass carp	*Ctenopharyngodon idella*
Roundtail chub*	*Gila robusta*
Bigmouth buffalo	*Ictiobus cyprinellus*
Redear sunfish	*Lepomis microlophus*
White bass	*Morone chrysops*
Yellow bass	*Morone mississippiensis*
Rainbow trout	*Oncorhynchus mykiss*
Sailfin molly	*Poecilia latipinna*
Flathead catfish	*Pylodictis olivaris*
Walleye	*Stizostedion vitreum*
Blue tilapia	*Tilapia aurea*
Mossambique tilapia	*Tilapia mossambica*

Table 1. Species detected since 1970 in target canals or the Salt River, now with connections via the CAP to the San Pedro and Gila Rivers, where these species have not been detected in AGFD monitoring. Taken from Clarkson (1999).	
Redbelly tilapia	*Tilapia zilli*
Razorback sucker*	*Xyrauchen texanus*
*Native fish, found in the Salt River. **Possible observation in the San Pedro River ***Found in the Salt River, but not in connecting canals to date.	

Table 2. Density and extent of distribution of species detected in the San Pedro and Gila rivers from 1995 to 1998. Summarized from USBR database.

Common name	Scientific name	Number of reaches found in	Average abundance in 200 meters	Found in San Pedro?	Found on Gila?
Longfin dace*	*Agosia chrysogaster*	7	7.82	+	+
Black bullhead	*Ameiurus melas*	2	1.61	+	-
Yellow bullhead	*Ameiurus natalis*	7	2.39	+	+
Sonora sucker *	*Catostomus insignis*	5	5.99	+	+
Red shiner	*Cyprinella lutrensis*	5	14.90	+	+
Carp	*Cyprinus carpio*	5	2.88	+	+
Threadfin shad	*Dorosoma petenense*	4	1.05	-	+
Mosquitofish	*Gambusia affinis*	7	5.36	+	+
Channel catfish	*Ictalurus punctatus*	5	2.07	+	+
Green sunfish	*Lepomis cyanellus*	7	1.42	+	+
Bluegill	*Lepomis macrochirus*	2	0.30	+	+
Smallmouth bass	*Micropterus dolomieu*	1	0.12	-	+
Largemouth bass	*Micropterus salmoides*	4	1.72	+	+
Desert sucker*	*Pantosteus clarki*	7	7.04	+	+
Fathead minnow	*Pimephalies promelas*	5	0.71	+	+
Black crappie	*Pomoxis nigromaculatus*	2	0.26	-	+
Flathead catfish	*Pylodictis olivaris*	2	0.68	-	+

RARE SPECIES

WHAT IS A RARE SPECIES?

The causes and consequences of species abundance and distribution have been at the heart of many ecologists' discussions over the last few decades. When plotting relative abundance vs. number of species a general pattern is found -a bell-shaped curve- (data arranged on a scale of logarithms to the base 2) that indicates the communities are dominated by a few common species, but also contain many rare species (Dobson 1996) This pattern is repeated even within communities with a variety of taxonomic groups in a wide range of habitats (Brown et al. 1995, Dobson 1996, Caley and Schluter 1997, Gaston and Kunin 1997). Citing difficulties in estimating abundance of rare species, ecological studies have concentrated on common species, describing species associations by using the most common members of the association (Grossman et al. 1998, Yant et al. 1984, Caley and Schluter 1997). At variance with this stance, the concept of rarity and its implications has attracted the attention of many individuals working in conservation biology (Arita et al. 1990, Gaston 1994, Kunin 1997, Maitland 1998; Cofré and Marquet 1999) and ecology of invasions (Kovalak et al. 1996, Moyle and Light 1996, Mack et al. 2000)

DIFFERENT USE OF THE TERM RARITY

Although rare species are regarded as those having low abundance and/or small ranges, a quick look at the biological literature dealing with the concept of rarity (and commonness) reveals a great variety of view points (Mayr 1963, Margules and Usher 1981, Rabinowitz et al. 1986, Soulé 1986, Ferrar 1989, Kunin 1997, Kunin and Gaston 1993, 1997, Rey-Benayas et al. 1999). In most cases, the definition of rare species is based on one, two or a few variables at most, which may include: abundance, range size, habitat specificity (= habitat occupancy), temporal persistence (e.g. taxon age), threat (probability of, or time to, extinction), gene flow, genetic diversity, endemism, or taxonomic distinctness.

The definition developed by Rabinowitz (1981; cited in Rabinowitz et al. 1986) is perhaps the most widely used for ecological discussions about rarity. She classified species based on three criteria: geographic range (large or small), habitat specificity (wide or narrow), and local abundance (somewhere large or everywhere small). A comparable analysis of rarity and abundance was undertaken by Reed (1992; cited in Dobson 1996), using data for Neotropical migrant bird species in North America.

Table 3. Rabinowitz's scheme for describing types of commonness and rarity using British wild flowers (from Rey-Benayas et al. 1999).

Geographic range	Wide		Narrow	
Habitat specificity	Broad	Restricted	Broad	Restricted
Abundance somewhere large	Common	Predictable	Unlikely	Endemics
Abundance everywhere small	Sparse		Non-existent	

Rabinowitz indicated that most species are abundant somewhere, and similarly, that most species have a wide geographic range. In addition, most species are rare in the sense that they are restricted to a single type of habitat. When considering the eight possible combinations of categories, only one (wide range, broad habitat specificity, and somewhere large local abundance) is classified as common. The other seven each include some form of rarity, and may not exist (Rey-Benayas et al. 1999).

More recently, Rey-Benayas et al. (1999) expanded on Rabinowitz' scheme for classifying species as common or rare by adding a fourth criterion, the ability of that species to occupy a larger or smaller fraction of its potential suitable habitats, i.e., habitat occupancy. Under this scheme, only one of the 16 combinations of species characteristics would be considered common: wide geographic range, broad habitat specificity, large local abundance, and frequent habitat occupation (Table 4).

Table 4. An expanded scheme for describing types of commonness and rarity proposed by Rey-Benayas et al. (1999).

Geographic range	Wide				Narrow			
Habitat specificity	Broad		Restricted		Broad		Restricted	
Abundance	Large	Small	Large	Small	Large	Small	Large	Small
Habitat occupancy high	Common	Widespread	Indicator		Locally common	Non-existent	Endemic indicator	
Habitat occupancy low	Highly dispersed	Sparse	Locally endangered		Potentially endangered		Endangered	

Note that the expansion of categories used adds three categories relating to endangerment. These categories arise because species that have narrow geographic and habitat needs are also at risk if they do not occupy much of the available habitat. Therefore, the scheme of Rey-Benayas et al. (1999) allows us to identify species that might have endangered status. Gaston (1997) argues that most operational definitions of rarity can be placed in a three-dimensional space, and a species rarity is defined by the existence of "threats" (e.g. risk of extinction, estimated time to extinction), "biology factors" (e.g. history, taxonomic isolation, abundance), and "human values" (e.g. how special species are).

DEFINITIONS OF RARITY RELYING ON EXISTENCE OF THREAT

Often the term rare is used as a category for species that are perceived in risk of extinction. Many natural resources agencies and conservation organizations list rare species within the group of species in need of protection as a third level of threat of extinction after endangered and threatened. These species may not be under direct threat, and may not be in decline, but are considered vulnerable for reasons described in state laws and lists that address rare species (California Department of Fish and Game, Idaho Department of Parks and Recreation, Environment Australia, Maine Department of Inland Fisheries and Wildlife, Rare Species Conservatory Foundation, South Dakota Department of Game, Fish, and parks, Swedish Threatened Species Unit, Texas Parks and Wildlife Department, Virginia Department of Conservation and Recreation).

The following are some of the operational definitions of rare:

Ashton (1976; cited in Munton 1987) Endangered and Threatened Amphibians and Reptiles of the United States
Those species that are considered rare throughout the state or are found in environmental conditions disjunct from the normal geographic range of the species.

Miller, R.R. (1972) Threatened Freshwater Fishes of the United States
Not under immediate threat of extinction, but occurring in such small numbers and/or in such a restricted or specialized habitat that it could quickly disappear.

Heintzelman, D. S. (1971; cited in Munton 1987) Rare and Endangered Fish and Wildlife of New Jersey
A rare species is not presently threatened with extinction, but it occurs in such small numbers in New Jersey that it may become endangered if its environment deteriorates further or other limiting factors change. Careful watch of its situation is essential.

Ayensu and De Philipps (1978, cited in Munton 1987) Endangered and Threatened Plants of the United States
A species that has a small population in its range. It may be found in a restricted geographic region or it may occur sparsely over a wide area.

Given (1981, cited in Munton 1987) Rare and Endangered Plants of New Zealand
Only small populations are known or the species is found only in restricted areas where it may be locally common. For the most part however the numbers of plants and localities where it is found are reasonably stable.

Tanasiyehuk, V.N. (1981; cited in Munton 1987) Data for the 'Red Book' of Insects of the USSR
Species not yet directly threatened with extinction, but occurring in small numbers or in such small areas they may rapidly disappear.

World Conservation Union (IUCN) (1986 Version)
Taxa that are not at present Endangered or Vulnerable but are at risk because of small total populations within the area of concern.

Colding and Folke (1997) The relations among threatened species, their protection, and taboos. Taxa with small world populations that are not at present "Endangered" or "Vulnerable," but are at risk. These taxa are usually localized within restricted geographical areas or habitats, or are thinly scattered over a more extensive range.

The definitions above use some of the same characteristics for rare species as described by Rabinowitz. The main factor used to classify a species as rare on the above definitions is low local abundance that in combination with wide geographic range but restricted habitat specificity or narrow geographic range regardless of habitat specificity reflect the types of rare species by Rabinowitz. However, this scheme does not discuss the term endangered species using the same attributes.

The scheme described by Rey-Benayas et al. (1999) allows for a more complex multi-level approach ranging from a common species to a truly endangered species. A rare species may be uncommon but able to occupy a large portion of its potential suitable habitat. If the same species occupies only a proportion of suitable habitat, it will be at risk of local extirpation or extinction (Table 4). Endangered species often present drastically reduced total number of individuals in their remaining populations. These type of populations are more vulnerable to the effects of inbreeding, loss of genetic diversity and fitness, which in turn may limit the species ability to reproduce and disperse within its potential habitat. This corresponds to the last three categories proposed by Rey-Benayas et al. (1999).

DEFINITIONS OF RARITY RELYING ON PARTICULAR BIOLOGICAL CHARACTERISTICS

Many attempts have been made to describe the biological and life history characteristics of rare species. It seems logical to think that by developing a framework by which a rare species could be defined, we could predict what species would be rare for any given habitat condition. However, although some important generalities have been found, many exceptions still occur, because rarity is an emergent trait of a species' population and its environment, and not a trait of an individual organism (Kunin 1997).

Scientists have explored the differences between rare and common organisms from a variety of stand points (breeding systems, reproductive investment, dispersal ability, homozygosity, competitive ability, resources usage, trophic status and body size) with a high concentration of plant studies, and very little on higher vertebrates (Rabinowitz 1986, Gaston and Lawton 1990a, McIntyre 1992, Gaston and Blackburn 1996, Gaston and Kunin 1997).

Conclusions from these studies reveal several important limitations in attributing rarity to particular biological characteristics. 1) Definitive reconstruction of a species' history is not possible. 2) Different operational definitions have been used in each study. 3) It is not possible to imply causation from association of rarity with one or multiple correlated factors (Gaston 1994, Gaston and Kunin 1997).

Despite careful development of theory for classifying species distributions, local abundance remains a ubiquitous but innocuous descriptor in scientific studies. Gaston (1994) compiled the criteria by which rare species have been delineated based on a great number of studies. These criteria could be quantitative (e.g. less than a thousand plants in any locality) or qualitative (e.g. recorded only occasionally) so that the proportion of species that are considered rare in a given community and/or study varies enormously (Gaston and Lawton 1990b, Kunin and Gaston 1993).

Although other elements of their biology may better characterize the condition of the species, when we set out to monitor rare species, the usual approach will focus on the low abundance of many rare species.. Thus, papers have been written on designing sampling strategies to detect rare species (Green and Young 1993, Kovalak et al. 1986). This approach represents the first step. Detection of a species allows us to answer questions about whether the spatial distribution is changing, or whether habitat use is shifting, for instance.

Trends in diversity of species may vary depending on the spatial scale being used. A basic and popular approach of assessing rarity is by developing distribution maps at different scales, although units of 10 km X 10 km are the standard (Spellerberg 1992). Different spatial scales in evaluating a community may produce different results. The abundances and range sizes of species are dynamic both in space and in time. This means that rarity is a scale-dependent concept. Species that may be rare in one area may not be so in another, and species which may be rare over an area of a particular size may not be rare over a larger or smaller area. Likewise, species which are rare in one time period may not be so in another, so our perception of a species' abundance may change when their abundances or range sizes are averaged over periods of differing duration (Kunin and Gaston 1997).

Similarly, different levels in the intensity of monitoring may provide different observations. Menges and Gordon (1996) examined three different levels of increasing intensity for monitoring rare plant species. Level 1 referred to species occurrence by mapping distributions of species and identifying the presence/absence or spatial extent of each population. Level 2 involves a quantitative assessment of abundance, often expressed as density, percent cover, or frequency. Level 3 was demographic monitoring of marked individuals, allowing quantitative assessments of demographic parameters, such as survivorship, growth and fecundity. While level 2 allows the analysis of population trends and hypothesizing about demographic mechanisms, level 3 allows modeling and population viability analysis. Depending upon conservation objectives, the three levels could be mixed in a study. For example a few populations of a species receives intensive level 3, while all populations receive a lower intensity of monitoring.

Probably the most comprehensive analyses on the attributes of rare and common species have been conducted by Gaston (1994 and 1997), Gaston and Kunin (1997), Kunin (1997), and Kunin and Gaston (1993 and 1997), who concluded that a rare species will usually present the following characteristics:

- Have breeding systems biased from outcrossing and sexual reproduction.
- Have lower reproductive investment
- Have poorer dispersal abilities
- Have higher levels of homozygosity
- Use less common resources and/or a narrower range of resources
- Have, for abundances, a greater probability of belonging to groups at higher levels of a trophic hierarchy
- Have, for abundances, under some circumstances, a greater probability of a larger body size, and for geographical range sizes, a greater probability of a smaller body size.

These attributes represent broad generalizations and should be carefully considered when attempting to identify rare species in a ecosystem. In the case of freshwater native fishes, Gaston and Lawton (1990a) indicated that the relationships between body size, geographic range size, and population density are weak and often non-existent. However, some North American desert fishes may exhibit a trend of small size and high abundance in isolated locations (Minckley and Deacon 1991).

In general, species with large geographic ranges have greater local abundances than those of restricted ranges. For some examples of benthic marine fishes, this pattern persists. However, for other fishes, small ranges and low abundances are the rule, possibly due to natural causes (specialized habitat requirements, trophic position, poor dispersal abilities, and patterns of range expansion after speciation) or a product of human activities (Gaston and Lawton 1990a). In their analysis of rarity, Gaston and Lawton (1990a) indicate that fish are different from most other taxa and may be more like plants by exhibiting three kinds of rarity explained by Rabinowitz: 1) widespread but sparce; 2) restricted by locally common; and 3) restricted and locally rare.

ASPECTS OF MONITORING AND ASSESSING RARITY

Any attempt to account for uncommon species in monitoring programs must immediately address the finite chance that such a species can go undetected, although it is present. This problem may affect whether we act as if the species is extirpated or whether we adequately describe the species assemblage at our research site.

Researchers, interested in the latter issue, have focused less on detecting particular species, and more on detecting as many species as possible (Lyons 1992, Angermeier and Smogor 1995, Paller 1995, Keating et al. 1998). In these cases, there is an assumption that failure to detect a specific rare species when it occurs is not necessary, but it is necessary to detect a certain proportion of the species that are present. Under these protocols, some less common species will be detected at one time, and another set will be detected at a different time. It may be that the same rare species go undetected each time, yet a high proportion of all species are, nonetheless, detected. This approach does not address monitoring for rare species. Lyons (1992), after finding no correlation between stream width and species richness, nonetheless recommended sampling 35 stream widths, or 3 riffle-pool sequences. Furthermore, Keating et al. (1998) demonstrated that different models for building species richness curves are very sensitive to species evenness and richness. Thus, quantitative attempts to include less common species into community descriptions are sensitive to the fact that these species are rare. This problem is greater in species with lower species diversity.

Other authors have directly addressed detection likelihood for particular species, and suggested study designs to detect specific rare species at a given level of probability (Elliot 1971, McArdle 1990, Green and Young 1993, Nicholson and Barry 1995). Solow (1992) and Nicholson and Barry (1995) each developed classical and Bayesian probabilities for concluding a species has been extirpated, based on the number of surveys since the species was last detected.

When trying to describe or model the spatial distribution of rare organisms, the negative binomial is the correct distribution. This distribution has two parameters, the average density *m* (for instance, the number of fish per sampled length of stream), and *k*, a measure of aggregation. The variance in density for organisms is:

$$s^2 = m + \frac{m^2}{k}$$

McArdle has consistently used the negative binomial in his papers on detection of species (McArdle 1990, McArdle et al. 1990).

Other workers regularly use the Poisson distribution, which is appropriate to describe counts of organisms that are randomly distributed in space. As the distribution of organisms goes from clumped to random, k becomes large, and

$$s^2 = m$$

which is the parameter for the Poisson distribution. The more exact negative binomial distribution, which describes both random and highly aggregated spatial distributions of organisms, requires additional sampling effort in order to estimate the degree of aggregation (*k*). Green has worked with the simpler Poisson distribution, arguing that it adequately replaces the negative binomial for very rare species (Green 1977, Green and Young 1993). Adequacy of the Poisson distribution means the costs of planning and carrying out a study are reduced.

Using the Poisson distribution, the formula

$$n = -\frac{1}{m}\ln\beta$$

describes the number of units to sample (*n*) for average density per unit (*m*), with probability of failure to detect (β). For instance, if researchers don't want to miss a particular species more than 5% of the time,

$$-\ln(\beta) \approx 3$$

so that

$$n = \frac{3}{m}$$

Using the above approximation for species occurring at the rate of 0.1 per sampling unit, n=30 sampling units would be needed to detect the species 95% of the time. There are surely rare species for whom such a large sample would be prohibitive. (Green and Young (1993) only tested the Poisson distribution against the negative binomial below this density, so this is their default definition of rareness.) Taking the liberty of extending the Poisson approach to species at higher densities than 0.1 per sampling unit, we may find a target density that is desirable to detect; this density must somehow be determined before sampling begins. In other words, even qualitative presence/absence information may not be attainable for very rare species.

Green and Young (1993) demonstrate the adequacy of the Poisson approximation for species occuring at a density below 0.1 per sample unit. At higher densities, clumping might mean the Poisson assumption does not reproduce results that the negative binomial would. In order for the Poisson assumption to come within 95% of the estimated sample number using the negative binomial,

$$\frac{m}{k} \le 0.107 .$$

Thus, the Poisson distribution describes approximately the same spatial pattern as the negative binomial when m is very small (an uncommon species) or if k (a measure of dispersion) is very large.

When we discuss the likelihood that we failed to detect a species when it was present, we are comparing our count of zero with other counts we could have obtained if the species were present. An alternative, Bayesian, approach is offered by Nicholson and Barry (1995), who extended McArdle (1990) by incorporating prior probabilities. Their specific example concerned detection of an invading species, the Manila clam *(Tapes philippinarum*). By adjusting their prior probability (based on opinions from biologists of the worst-case scenario), they can explore the consequences of adding or removing any number of samples from a protocol. Similarly, Nicholson and Barry (1995) use this approach to address the likelihood that a species is not present after several sampling periods in which the species was not detected.

In order to go beyond detection of species and ask whether the species abundance is stable, we will have to quantify how common they are. Kovalak et al. (1986) discuss number of sample units needed to obtain specified confidence limits on estimates of mean density. Kovalak et al. (1986) provide an estimate for number of samples needed to achieve a given precision in density estimate. Their equation is a simplification of the following formula from Zar (1996):

$$n = \frac{t_{\alpha}^{2}\sigma^{2}}{L^{2}}$$

where L is the half-width of the confidence interval. L can be expressed as a certain proportion of the mean. For instance, for a rare species of density m = 0.1/m^2, assuming the Poisson distribution so that σ^2=mean, to get a confidence interval that is ±10%,

$$n = \frac{1.96^2(0.1)}{(0.1*0.1)^2}$$
$$= 3841$$

Note that whereas 30 samples would be required to detect the species 95% of the time when it is present (see above), almost 4000 samples would be required to describe the density of the species with this level of precision.

This point of diminishing returns represents the measure against which a monitoring program would set their thresholds. Given that a species might invade a monitored system, a mean density must be chosen that represents the minimum detectable limit. Similarly, a monitoring program that may subsequently declare a species has been extirpated must first declare the density below which that species will be considered vanished; additional effort will not be expended to detect the species below this density.

BIOLOGICAL INVASION

One of the major phenomenon in our planet that has drastically changed the distribution and abundance of living things, and the structure and function of natural ecosystems over the last 200 years is biological invasion. Biological invasion is defined as the geographic expansion of a species into an area not previously occupied by that species (Mack et al. 2000). Invasions may be the result of climatic changes and tectonic changes as well as human activities. Alien species (a.k.a. non-indigenous, nonnative, exotic, or introduced species in a general sense) come from a donor biota or region, and enter a recipient one (Vermeij 1996). The extended and profound impacts of some invasive species in the ecosystems and local economies have captured the attention of the public. Zebra mussels from Europe cause severe damage to the shipping industry and electricity-generating plants around the American Great Lakes, ctenophores from the western Atlantic threaten fisheries in the Black Sea, rabbits from Europe and cactuses from North America drastically alter the Australian bush, South American fire ants devour native ants and affect the gardening practices of home-owners in the southern United States, and the North Atlantic sea lampreys decimate lake trout populations in the Great Lakes. Few places on earth remain free of species introduced by humans; even fewer could be considered immune from this dispersal. From the examples above, we can say that invading species include multiple taxa and could come from many geographic regions. In the U.S. alone, millions of dollars have been spent in attempting to eradicate some of the most insidious invaders and prompting the creation of special eradication programs and guidelines at the regional, national, and international levels (Aquatic Nuisance Species Task Force, Federal Interagency Committee for the Management of Noxious and Exotic Weeds, Aquatic Nuisance Species Task Force, Precautionary approach to the introduction and transfer of aquatic species [Bartley and Minchin 1995], IUCN Guidelines for the Prevention of Biodiversity Loss Due to Biological Invasion [IUCN 1999]), or special legislation (National Invasive Species Act of 1996 amending the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990, 1999 Presidential Executive Order on Invasive

Species, National Strategy for Invasive Plant Management) (see web sites for U.S.Fish and Wildlife Service-Invasive Species Program, U.S. Geological Survey-Upper Midwest Environmental Sciences Center, National Biological Control Institute, National Biological Information Infrastructure).

Humans, through migration, transport, and commerce, have acted as both accidental and intentional dispersal agents of many invading species. Although in general we are aware that human-caused invasions have resulted in the extirpation or extinction of native organisms (Taylor et al. 1984, Meffe 1985, Moyle 1995). However, many other invading species have become established without extinctions of native organisms and seem to have become integrated into the local biota (Brown 1989, Carey 1996, Cox 1999). These observations make our ability to predict outcomes of biological invasions quite limited.

WHAT IS AN INVASIVE SPECIES?

An invasive species (a.k.a. invading species) is an organism that crosses barriers (with or without help from humans), rapidly establishes itself on the other side, then expands its numbers and range in its new habitat and persists (Brown 1989, Mack et al. 2000).

Several attempts have been made to describe the attributes of a successful invader (Newsome and Noble 1986, Brown 1989, Ehrlich 1989, Case 1996, Vermeij 1996, Williamson and Fitter 1996, Mack et al. 2000). Here is a summary of those attributes:

Attribute	**Successful invader**	**Unsuccessful invader**
Geographic range	Large	Small
Abundance	High in original range	Rare in original range
Mobility	Vagile	Sedentary
Ability to disperse	High	Low
Duration of generation times	Short	Long
Ability to shift between r and K strategy	High	None
Genetic variability	High	Low
Social pattern	Gregarious	Solitary
Role of female	Female able to colonize alone	Female unable to colonize alone
Body size	Larger than most relatives	Smaller than most relatives
Association/dependency with humans	High	Not associated
Adaptability	Able to function in a wide range of physical conditions	Only able to function in a narrow range of physical conditions
For Birds		
Flock size	Travel in small flocks	solitary
Diet	Granivore	Insectivore

Attribute	Successful invader	Unsuccessful invader
Habitat preferences	Able to shift	Unable to shift
For Plants		
Vegetative reproduction	Common and often the only method of reproduction	Rare
Reproduction rate	fast	Slow

Similar to the attributes described for a rare species, those for an invasive species should be carefully considered when attempting to identify this type of species. Biological attributes alone are not enough to ensure a successful invasion. Other factors such as size of the initial immigrant population, frequency of immigrations, sex ratio, maturity of individuals, genetic composition, behavioral patterns, ability of new immigrants to escape predation and parasites, disturbances before and after initial immigration, timing (particular season or weather conditions), and more importantly, vulnerability/resistance (vacant niches) of the community being invaded also play an important role (Mooney and Drake 1986, Baltz and Moyle 1993, Chapman and Carlton 1994, Leach 1995, Lyons et al. 1995, Grozhloz 1996, Hastings 1996a and 1996b, Johnson and Carlton 1996, Kot and van den Driessche 1996, Mackie and Schloesser 1996, Moyle and Light 1996, Rejmanke and Richardson 1996, Williamson and Fitter 1996).

INVASION PROCESS OR THEORY OF INVASION

The process of invasion has been described using different viewpoints; however, most of these approaches could be conceptualized in three successive stages (Arthington and Mitchell 1986, Vermeij 1996, Mack et al. 2000). The first one is the arrival stage when organisms (colonizing species) are transported from their native ranges to a new region. This may occur naturally or with the aid of humans. At this stage, many, if not most, perish en route to a new locale. If they succeed in reaching a new site, immigrants are likely to be destroyed quickly by a multitude of physical or biotic agents (Mack et al. 2000). The second stage, establishment, occurs when the new population sustains itself by local reproduction and recruitment, which in turn augments or replaces dispersal from the donor region as a mean for the invading population's persistence (Vermeij 1996). Finally, integration (or naturalization) occurs when the invading species integrates with other species in the recipient region and there is no dependence on re-immigration from the native range. Among the naturalized species that persist after this extremely severe reductive process, a few will go on to become (Mack et al. 2000). Animal invaders can cause extinctions of vulnerable native species through predation, grazing, competition, and habitat alteration. Many non-native animals and plants can hybridize with native species (Downling and Childs 1992, Cox 1999, Huxel 1999).

Mack et al. (2000) argue that the progression from immigrant to invader often entails a delay or lag phase, followed by a phase of rapid exponential increase that continues until the species reaches the bounds of its new range and its population growth rate slackens. Several examples exist where only a brief lag phase has occurred (e.g. Africanized bees in the Americas and zebra mussels in the Great Lakes). In other cases, the lag phase has been quite extended (sometimes for decades) during which the invaders may remain undetected (e.g. Brazilian pepper trees in Florida).

During the lag phase, it can be difficult to distinguish doomed populations from future invaders. Most extinctions of immigrant populations occur during the lag phase, yet the dynamics of such a population are often indistinguishable from those of a future invader, which is growing slowly but inexorably larger. This similarity in the size and range makes quite difficult any attempt to predict future invaders while they are few in numbers and presumably controllable (Mack et al. 2000).

Another active area of research on invasive species, over the last two decades, has been focussed on the attributes of the recipient community that may facilitate the establishment of invaders. Brown (1989) described five patterns of succesful invasion among vertebrates:

1. Isolated environments with a low diversity of native species tend to be differentially susceptible for invasion.
2. Species that are successful invaders tend to be native to continents and to extensive, nonisolated within continents.
3. Successful invasion is enhanced by similarity in the physical environment between the source and target areas.
4. Invading exotics tend to be more successful when native species do not occupy similar niches.
5. Species that inhabit disturbed environments and those with a history of close association with humans tend to be more successful in invading man-modified habitats.

Further analyses of the characteristics of both donor and recipient communities have been explored by Kruger et al. (1989), Loope and Muellr-Dombois (1989), Mack (1989), Baltz and Moyle 1993, Smallwood (1994), Hastings (1996), Vermeij (1996) and Mack et al. (2000).

Following the lead of workers in the field of disease transmission, much of the current work on invasions focuses on predicting the pattern of invasions (Mollison 1977, Kornberg and Williamson 1987, Chapman and Carlton JT 1994, Hastings 1996, Carey 1996, Kareiva et al. 1996).That is, given characteristics of the invading species and of the area it has recently established itself, which areas will be occupied and in which sequence? What densities are expected to occur? This latter question allows researchers to estimate the effort they will expend in detecting individuals of the species.

DISCUSSION

Our initial idea that both endangered natives and recently introduced non-natives might be studied under the framework of rarity resulted only partially true. Endangered species share some traits with rare species in the sense that both might have low abundance and may have limited geographic range. While habitat specificity and occupancy may vary between a rare and an endangered species, both are limited in their reproductive and dispersal capability to successfully expand their ranges and/or increase population size, which makes them more similar with each other than a rare species with an invasive species. By comparing invasive species attributes with those used in Rabinowitz's and/or Rey-Benayas' schemes of rarity, we can say with confidence that rare species and invasive species present almost opposite characteristics.

The Gila and San Pedro rivers seem highly vulnerable for invasion when considering factors like habitat modifications, already depauperate fish fauna, presence of alien species, proximity to urban developments, and the presence of the CAP as a potential corridor for alien species. The presence of alien fishes in the CAP and portions of the Gila and San Pedro rivers does not necessarily indicate those species have become established. They may be simply showing up in the system because of the continuous supply of individuals coming from the CAP, and not because of successful recruitment events that will allow them to persist. However, they can invade to a river in a propitious year, anyway.

Our knowledge about the ecology and epidemiology of invasion by alien species in desert aquatic systems is limited. A more comprehensive and systematic rather than an anecdotal approach is badly needed. Each potential invading species should be considered on a case-by-case basis. This approach should be tested at several spatial and temporal scales during the various stages of invasion and considering various class sizes (larvae, juvenile, and adult) for each target species. In addition, this approach could be complemented by experimental manipulations based on innocuous releases of organisms under controlled situations.

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