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Biological collections and ecological/environmental research: a review, some observations and a look to the future

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ABSTRACT

Housed worldwide, mostly in museums and herbaria, is a vast collection of biological specimens developed over centuries. These biological collections, and associated taxonomic and systematic research, have received considerable long-term public support.

The work remaining in systematics has been expanding as the estimated total number of species of organisms on Earth has risen over recent decades, as have estimated numbers of undescribed species. Despite this increasing task, support for taxonomic and systematic research, and biological collections upon which such research is based, has declined over the last 30-40 years, while other areas of biological research have grown considerably, especially those that focus on environmental issues.

Reflecting increases in research that deals with ecological questions (e.g. what determines species distribution and abundance) or environmental issues (e.g. toxic pollution), the level of research attempting to use biological collections in museums or herbaria in an ecological/environmental context has risen dramatically during about the last 20 years. The perceived relevance of biological collections, and hence the support they receive, should be enhanced if this trend continues and they are used prominently regarding such environmental issues as anthropogenic loss of biodiversity and associated ecosystem function, global climate change, and decay of the epidemiological environment. It is unclear, however, how best to use biological collections in the context of such ecological/environmental issues or how best to manage collections to facilitate such use.

We demonstrate considerable and increasingly realized potential for research based on biological collections to contribute to ecological/environmental understanding. However, because biological collections were not originally intended for use regarding such issues and have inherent biases and limitations, they are proving more useful in some contexts than in others. Biological collections have, for example, been particularly useful as sources of information regarding variation in attributes of individuals (e.g. morphology, chemical composition) in relation to environmental variables, and provided important information in relation to species' distributions, but less useful in the contexts of habitat associations and population sizes.

Changes to policies, strategies and procedures associated with biological collections could mitigate these biases and limitations, and hence make such collections more useful in the context of ecological/environmental issues. Haphazard and opportunistic collecting could be replaced with strategies for adding to existing collections that prioritize projects that use biological collections and include, besides taxonomy and systematics, a focus on significant environmental/ecological issues. Other potential changes include increased recording of the nature and extent of collecting effort and information associated with each specimen such as nearby habitat and other individuals observed but not collected. Such changes have begun to occur within some institutions.

Institutions that house biological collections should, we think, pursue a mission of 'understanding the life of the planet to inform its stewardship' (Krishtalka & Humphrey, 2000), as such a mission would facilitate increased use of biological collections in an ecological/environmental context and hence lead to increased appreciation,

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encouragement and support from the public for these collections, their associated research, and the institutions that house them.

Key words: biological collection, museum, herbarium, ecology, environment.

CONTENTS

I. INTRODUCTION

Housed mostly in museums and herbaria throughout the world is a vast collection of biological specimens that has been built up over centuries. People have been collecting and accumulating biological specimens to display publicly for some 300 years, at least since Czar Peter the Great opened a museum in 1719 containing everything from a butterfly collection to live abnormal *Homo sapiens*. Today, there are an estimated 2.5-3 billion biological specimens in total (Soberon, 1999; Krishtalka & Humphrey, 2000; O'Connell, Gilbert & Hatfield, 2004). This assemblage of specimens constitutes an invaluable record of the evolution of life and has, beginning with taxonomy and systematics (Simpson, 1961; Mayr, 1968), provided the basis for much biological research; to many, it has been fundamental and essential in this regard (Harvey, 1991; Idema, 1993; Renner & Ricklefs, 1994; Mallet & Willmott, 2003; O'Connell *et al.*, 2004; Winker, 2004). Most importantly, taxonomy and systematics enable other biological research to be compared and integrated (Winker, 2004). It may, for example, be reasonable to combine the results of research carried out on the same or related species in different situations (Danks, 1988; Ehrlich & Hanski, 2004). The addition of an evolutionary framework has helped us to understand the origins of the biological patterns we observe and how these patterns change through time (Ehrlich & Raven, 1964; Mayr, 1968; Danks, 1988).

The huge biological collections, and their associated systematic research, have received considerable support from the general (i.e. non-scientific) community for a long period of time. In many countries, publicly funded museums and herbaria were established over 100 years ago to house regional or national biological collections and those who maintain or study them (Briggs, 1991; Allmon, 2004). One of the oldest of these, the Natural History Museum in Kensington (London), associated with the British Museum, was founded in 1756 and housed in its present quarters in 1881. Arguably the most famous natural history museum, it has always been funded primarily through the British government. Among other early and well known Museums and Herbaria in Europe and North America are the Muséum d'Histoire Naturelle in Paris (established 1793), the Humboldt Museum (Museum für Naturkunde) in Berlin (1810), the Academy of Natural Sciences in Philadelphia (1812), the Botanische Staatssammlung München (1813), the Gray Herbarium at Harvard (1840s), Royal Botanic Gardens, Kew (1853), the Missouri Botanical Garden (1856), the American Museum of Natural History in New York (1869), Natural History Museum (Naturhistorisches Museum) in Vienna (1891, but insect collections trace to 1793), the Jepson Herbarium of the University of California (1890s), the Field Museum of Natural History in Chicago (1893), and the U.S. National Museum of Natural History (1910). Some museums and herbaria in other parts of the world were also established over 150 years ago (e.g. Indian Museum, Calcutta, 1814; National Museum of Brazil, Rio de Janeiro, 1818; Australian Museum, Sydney, 1827). Of course, many of these institutions have received additional income from other sources such as admissions fees, the sale of items, and charges to researchers for bench space, but for the most part they have been supported by the public purse.

The apparent work remaining to be done in taxonomy and systematics has, if that work is viewed as continuing the description of all of biodiversity, been getting larger as the estimated total number of species of organisms on Earth has generally risen over recent decades, as have estimates of the numbers of undescribed species. About 25 years ago the estimated number of world species was put at about

3-5 million (Raven, 1983). In 1988 this estimated number was revised upwards to 30-50 million (May, 1988), but more recent estimates have been somewhat lower at about 10-15 million (Hammond, 1992; Stork, 1999). As the total number of described species has increased less dramatically over the same period (May, 1988; Stork, 1999), the estimated number of undescribed species has generally increased.

However, despite this apparently increasing task size, support for taxonomic and systematic research has declined over about the last 30-40 years. Government funding of institutions where taxonomic and systematic research has been based has, allowing for inflation, been steadily declining over this period, and with this decline in funding, there have been associated declines in the numbers of taxonomists and systematists, and in the level of maintenance for existing collections (Gee, 1990; Idema, 1993; Miller, 1994; Dalton, 2003; Froelich, 2003; Stokstad, 2003). This decline has been particularly severe within Universities and appears to be continuing (House of Lords Select Committee on Science and Technology, 2002; Gropp, 2003; Joseph, 2006).

On the other hand, over about the same period, other areas of biological research have experienced considerable growth, especially those that focus on environmental issues (Briggs, 1991; Idema, 1993; Mikkelsen & Cracraft, 2001). Awareness of environmental deterioration and its underlying human causes has increased sharply since the 1960s (Carson, 1962; Ehrlich, 1968) and been further boosted by the widespread recognition of human-induced global climate change (Hughes, 2000; McCarty, 2001; Walther *et al.*, 2002; Root *et al.*, 2003).

Reflecting this general increase in research that focuses on ecological questions (e.g. what determines the distribution and abundance of a species) or environmental issues (e.g. effects of toxic pollution), there has been a dramatic rise during about the last 20 years in the level of research that attempts to use biological collections in museums or herbaria in an ecological/environmental context. Up until 1985 this was infrequent (Fig. 1, Fisher, 1937; Lack, 1946; Snow, 1956), though the early investigations of the thinning of shells of birds' eggs in relation to pesticide use (Ratcliffe, 1967; Hickey & Anderson, 1968; Grier, 1982), and of mercury levels in fish and birds (Berg *et al.*, 1966; Miller *et al.*, 1972) illustrated the kind of collection-based environmental research that is possible. Since 1985 there have been about 400 scientific publications (by our count) that report or discuss the use of biological collections in relation to ecological/environmental issues such as criteria for selecting areas for conservation, species decline, biogeography and climate change. These publications have been occurring at an increasing rate (Fig. 1). Of course, this use of biological collections has been and continues to be greatly facilitated by the introduction and development of computer technology and the establishment and linking of computerized databases (Morin & Gomon, 1993; Soberon, 1999; Winker, 1999; Edwards, Lane & Nielsen, 2000; Graves, 2000; Graham *et al.*, 2004). This is now happening on a global scale through programs such as the Global Biological Information Facility (GBIF) (Edwards, 2004).

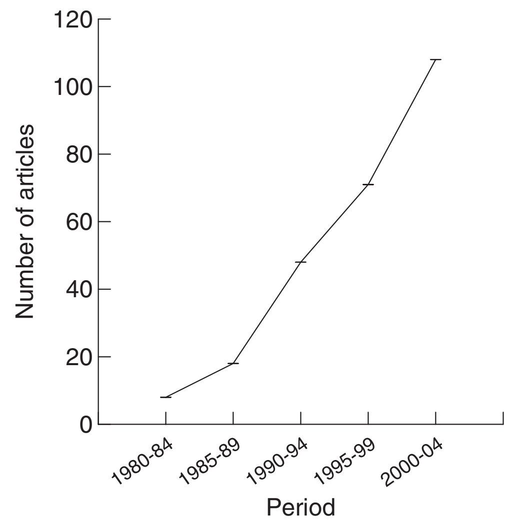

Fig. 1. Numbers, per five-year period, of published articles using biological collections to address ecological/environmental issues.

It seems likely that the perceived relevance of biological collections will be enhanced in the future if they are used prominently in the context of environmental issues, such as anthropogenic loss of biodiversity and associated ecosystem function, global climate change, and the decay of the epidemiological environment (Hoagland, 1989; Duellman, 1992; Drinkrow, Cherry & Siegfried, 1994; Cotterill, 1995; Daily & Ehrlich, 1996; Krishtalka & Humphrey, 2000; Ehrlich, 2005). Such research would complement the roles of biological collections in providing phylogenetic and phylogeographic information and hence enhancing our understanding of the processes and outcomes of evolution, in the provision of basic natural history information, and in contributing to our knowledge of species' distributions.

It is not clear, however, how best to use biological collections in the context of ecological/environmental issues, as there has been no detailed and comprehensive review of this aspect of collection-based research. Such a review could identify the range of possible ecological/environmental issues that may be addressed using biological collections, and modifications to procedures associated with such collections that may enhance their usefulness in this regard. Our aim is to provide such a review, and to consider the future maintenance and employment of museum collections in this context. Other reviews of biological collections have focused on particular aspects of these collections, rather than being as comprehensive as possible (Shaffer, Fisher & Davidson, 1998; Green & Scharlemann, 2003; Graham *et al.*, 2004; Suarez & Tsutsui, 2004). We consider ecological questions and environmental issues together as they are closely interrelated and often without clear distinction between them.

II. METHODOLOGY

To obtain bibliographic information concerning relevant scientific literature, we used *Zoological Record*, a computerized database of the zoological literature published since 1978, *BIOSIS Previews*, a more general bibliographic database, for botanical literature since 1980, and followed citations from one article to another. We used these databases to search for articles for which the words "collection" and "museum" or "herbarium/herbaria" appeared in the title, abstract or key words. We then examined the abstract and/or title of each article, eliminating those that did not seem relevant. We subsequently obtained copies of as many as possible of the remaining articles and those that the trail of citations led us to. The present review is based on this final collection of roughly 600 articles, which, as will be seen below, is strongly biased towards vertebrate animals, especially birds and mammals. We found, however, a high level of consistency across all kinds of organisms in terms of the issues we discuss. In preparing this review, we have followed the strategy described in Pyke (2001) and illustrated in several previous reviews (Pyke & White, 2001; Pyke, 2002; Pyke & Read, 2002), and used the bibliographic computer software package *Endnote* (version 10).

III. REVIEW

(1) Nature, extent and accuracy of information available in biological collections

The extent to which general biological collections can provide information of a geographic nature depends upon the distribution and intensity of collecting effort across landscapes and waterscapes, and is often limited (Illoldi-Rangel, Sanchez-Cordero & Peterson, 2004; Van Gemerden *et al.*, 2005). For the most part, collections were made in a haphazard and opportunistic manner, largely dependent on the particular interests of the collector (Rautenbach, 1979; Soulé, 1990; Ponder *et al.*, 2001; Schmidt *et al.*, 2005). As a result collections have mostly been made near centres of human activity and along the roads that join them, many areas have been under-sampled, substantial regions may not have been sampled at all, and numbers of recorded locations may be low (Kress *et al.*, 1998; MacDougall *et al.*, 1998; Soberón, Llorente & Oñate, 2000; Steege, Jansen-Jacobs & Datadin, 2000; Parnell *et al.*, 2003; Kadmon, Farber & Danin, 2004).

Such problems may be reduced, at least in part, by combining the information that is available in collections in different institutions (Soberon, 1999; Krishtalka & Humphrey, 2000) and including observational (i.e. non-specimen) records of species along with specimen-based records. In almost all studies where specimen collection locations have been of interest, the available information from collections in different institutions has been combined (Buss & Yund, 1988; Soberón *et al.*, 2000; Anderson, Gomez-Laverde & Peterson, 2002; Pyke, 2002; O'Connell *et al.*, 2004). Specimens from different collections have also been combined in studies of the prevalence of abnormal or injured individuals (Jurmain, 1997; Johnson *et al.*, 2003; Mallory *et al.*, 2004). Observational records have been combined with specimen-based records in many studies (Prendergast *et al.*, 1993a; Reznick, Baxter & Endler, 1994; Godown & Peterson, 2000; Davidson, Schaffer & Jennings, 2002; Pyke, 2002; Davidson, 2004), but this is only possible where species identification by observation without collecting is reasonably reliable (Swift *et al.*, 1993; Fagan & Kareiva, 1997).

The manner in which biological collections can be used in the context of environmental issues and ecological questions depends on the nature of the information that is associated with each specimen (Ehrlich, 1964; Lane, 1996; Fisher & Warr, 2003; Hromada *et al.*, 2003). Typically, each specimen or sample (e.g. multiple fish from a 'collecting station') has an attached label (or labels) upon which is recorded the collection date and location, the name of the collector, the identity of the specimen (e.g. species/sex), and the name of the person who made the identification (Hromada *et al.*, 2003). Sometimes, there may be additional information, such as sex, morphological measurements, a description of the habitat where the specimen was collected or a description of the behaviour of the plants or animals at the time of collection (e.g. plants: emitting odour; animals: calling, feeding) either on an attached label or in associated field notes recorded by the collector (Morin & Gomon, 1993; Reznick *et al.*, 1994; Soberon, Llorente & Benitez, 1996). It may also be possible to obtain information by further examination of an existing specimen (e.g. parasites, disease, stomach contents, chemical composition, morphological abnormalities) (Green & Scharlemann, 2003; Hromada *et al.*, 2003; Mey, 2003).

The use of biological collections is, however, often restricted by the absence of available information associated with each specimen. It is rare, for example, for specimen labels, and hence computerized collection databases, to include information about nearby habitats of the plant or behaviour of the animal at the time it was collected (Hromada *et al.*, 2003). It is also unusual for detailed information to be recorded about the collection methods or effort employed, or about which encountered or captured individuals were collected and which ones were not. It is also often difficult to know which specimens were collected in the same location at the same time. Such gaps limit the extent to which biological collections can yield information about species abundance in general, species absence in particular and patterns of species co-occurrence. In some cases, a person collecting a specimen may have recorded additional associated information or taken associated photographs, but these activities have generally been carried out in the context of the person's research interests, and the resulting information has tended to remain in field records or personal photographic collections and not become generally available (H. Cogger, personal communication). Where available, such ancillary information can significantly enhance more recent research (e.g. see http://mvz.berkeley.edu/Grinnell_Method.html).

The use of biological collections may also be restricted by the accuracy or detail of available information (Murphey *et al.*, 2004). For example, the location where a specimen was collected may be known, at one extreme, to within a few meters or, at the other extreme, specified only at a very broad geographic scale. Unless location coordinates are determined [e.g. with a portable global positioning system (GPS) unit] and recorded at the time of collection, location descriptions (e.g. x km west along road y from intersection with road z) must be subsequently translated into location coordinates, a process that has been labeled 'georeferencing' or 'geocoding' (Theodorakis, Blaylock & Shugart, 1997; Peterson *et al.*, 2000; Soberón *et al.*, 2000; Illoldi-Rangel *et al.*, 2004; Chapman & Wieczorek, 2006). Reported quantitative estimates of the accuracy, with which recorded locations are known, range from 200 m to 1.1 km (0.1 min, Peterson *et al.*, 2000; 1.1 km, Soberón *et al.*, 2000; e.g., 0.01 degrees, Illoldi-Rangel *et al.*, 2004) and various approaches have been developed for describing and calculating the spatial accuracy associated with location records (Guo, Liu & Wieczorek, 2008). Information about habitat can also vary enormously (Hansen & Richardson, 1999).

Conclusions that can be drawn from biological collections may also be limited by inherent biases in the ways collections are made or maintained (Ponder *et al.*, 2001). Collections may be biased with regard to the appearance of potential specimens, with unusual specimens being chosen over ones with a more common appearance (Ehrlich, 1964; Mallory *et al.*, 2004), although the opposite could occasionally be the case, or with individuals of particular recognizable age/sex categories preferentially collected or avoided (Snow, 1956). In butterflies, for example, "worn" specimens are often excluded from series, giving the samples a phenological bias (time from eclosion can be estimated by wear patterns). Collections may be biased in terms of the size or magnitude of whatever is being collected (Rodgers, 1990; Levitan, 1992). For example, collectors of birds' eggs have sometimes preferentially chosen larger over smaller clutches (Lack, 1946). Collections may show seasonal bias, either because of seasonal collecting patterns or other biases such as the butterfly wing wear example mentioned above. More collecting may, for example, occur during certain school or University holidays than at other times (G.H. Pyke, unpublished). A tendency for relatively large, and hence preferred, clutches of birds' eggs to occur at a different time of year from smaller clutches could have biased collection dates for eggs (Lack, 1946). Conversely, seasonal biases may lead to other biases (e.g., Takeuchi & Koganezawa, 1994). Biases may also result from preferential discarding of specimens, as when the Keeper of Entomology at the British Museum bragged of buying many collections, saving the "aberrations," and throwing out the 'junk' (Ehrlich, 2005). That made it impossible to determine, for instance, what the frequencies of melanic individuals were at various times in the past for a species of great evolutionary-ecological interest, *Biston betularia*. There also could be a bias with regard to whether there are signs of disease (Antonovics *et al.*, 2003). In short, sampling biases are a major reason for the limited utility for answering many important questions that could be asked of the three billion specimens housed in museums and herbaria.

Despite these limitations, which we shall discuss separately in greater detail below, there have been many studies that use biological collections in the context of environmental issues or ecological questions. Depending on the approach taken, these studies can be categorized as follows: (*a*) population size; (*b*) distribution of particular species (e.g. changes through time; relationships with other variables); (*c*) identities and/or numbers of species that occur in particular areas; (*d*) habitat & behavior; (*e*) individual attributes (e.g. sex/age, morphology, diet, habitat).

We shall discuss each of these categories separately.

(*a*) *Population size*

Determining spatial and temporal patterns of population size, what factors control these patterns, and how these factors operate, are among the most fundamental issues in ecology. Such knowledge and understanding are essential in the control of pest species, in stopping and reversing the decline of threatened species, management of a population for any purpose, or understanding the role of particular species as bio-indicators of environmental quality and change.

It is difficult, however, because of the collecting biases and lack of information described above, to use biological collections to consider aspects of population size. For example, because of patchy and biased collecting and lack of information concerning collection effort and methods, it is difficult or impossible to use specimen numbers to estimate relative or absolute abundance of populations or species (Bickel, 1999; Baldwin *et al.*, 2004). Because of a lack of habitat information concerning collection locations, it is not generally possible to relate the numbers or kinds of individuals collected to the nature or extent of adjacent or nearby habitat (Hansen & Richardson, 1999).

It is therefore not surprising that there have been very few attempts to draw conclusions from biological collections in terms of population size, and only in situations where the above problems could be overcome or were ignored. For example, after standardizing for variation in collection effort, analysis of long-term collection data for fish in the Pearl River drainage in the USA indicated that populations of some species have declined significantly since the 1960s while those of other species have increased over the same period (Piller, Bart & Tipton, 2004). However, this was only possible because all the specimens, numbering about 700, 000 in total, had been collected by the same two individuals who maintained the same collecting regime over a long period of time (i.e. 1950 to 1988) (Piller *et al.*, 2004). An examination of mammal specimens collected over about the last 100 years from a region around Chicago, USA indicated that the relative abundances of species that use prairie and open grassland habitat have declined dramatically while those of species that use wooded habitats have increased, as would be expected from the disproportionate loss of prairie habitat and increases in woody vegetation within grasslands in the region (Pergams & Nyberg, 2001). However, implicit in this study is the assumption that there has been no change in species or habitats preferentially targeted for collection and, while departures from this assumption seem unlikely to alter the general conclusions of the study, they could modify them quantitatively and make it impossible to detect more subtle changes. Increases and decreases in species abundances were detected for a number of Japanese plant species on the basis of the ratio of the number of collected specimens for each species to the total numbers of collected specimens for all species (Miki *et al.*, 2000).

(*b*) *Distributions and abundances of particular species*

Knowing what factors control the distribution of a species and how these factors operate is also a fundamental ecological issue. Though arguably a special case of the general population-size issue, approaches to population size generally omit consideration of zero numbers or species absence whereas considerations of species distribution focus explicitly on the presence/absence dichotomy. Because they provide information in relation to species presence/absence rather than population sizes (see below), biological collections are more likely to be relevant in the context of species distributions than in the context of population sizes.

Biological collections contribute a great deal to our knowledge of the geographic distributions of many species. For many taxa, both vertebrate and invertebrate, field guides and taxonomic monographs often rely heavily on this source of information regarding recorded locations. For some taxa, collections provide the only source of data regarding distribution. Biological collections can potentially provide important information about past distributions of species, so long as collection locations are known or can be determined with reasonable accuracy (Allen *et al.*, 2001). Changes in species distribution can sometimes be determined by revisiting and surveying sites or areas where a species was previously collected (Fellers & Drost, 1993; Drost & Fellers, 1996; Fisher & Shaffer, 1996).

Despite the difficulties discussed above, biological collections have provided useful information in relation to declines and increases for some species. Through both comparisons between different time periods within collections and between collections and recent surveys it has been possible, in a large number of cases, to record the disappearance of some species from some areas and the resulting contractions in range for these species (Drost & Fellers, 1996; Fisher & Shaffer, 1996; Turner *et al.*, 1996; Catling & Larson, 1997; Chaudhary & Rao, 1998; Joye, Castella & Lachavanne, 2002; Lienert, Fischer & Diemer, 2002). It has similarly been possible to record increases in distribution of some indigenous species (Laughlin, 2003) and the spread of feral or alien species following introduction (Johnston & Selander, 1964; Selander & Johnston, 1967; Fraile *et al.*, 1997). More subtle changes in abundance have not, however, been detected through such comparisons (Baldwin *et al.*, 2004).

Museum collections have also been used, often in combination with other non-specimen records, to understand and predict distributions of species. Here, it is assumed that the ecological 'niche' of a species, and hence whether or not a species can occur at a particular location, is a function of both biotic and non-biotic parameters for this location, and mathematical/statistical methods are used to determine these functional relationships (Godown & Peterson, 2000; Peterson & Vieglais, 2001; Anderson & Martinez-Meyer, 2004; Illoldi-Rangel *et al.*, 2004; Rovito, Arroyo & Pliscoff, 2004; Vargas *et al.*, 2004). When such models are applied to locations not already surveyed for a species in question, the suitability of these locations for this species can be predicted and, in this way, the overall distribution of suitable locations for a species can also be predicted (Peterson *et al.*, 2000; Anderson *et al.*, 2002; Anderson, 2003; Anderson & Martinez-Meyer, 2004). Such prediction of likely or potential distributions for feral or alien species before they are introduced may help with evaluation of the environmental risk they pose (Sanchez-Cordero & Martinez-Meyer, 2000; Peterson & Vieglais, 2001; Arriaga *et al.*, 2004; Iguchi *et al.*, 2004). The likelihood that a species will occur in a particular suitable location may depend on past history regarding its distribution or its likely ability to disperse from other locations where it occurs (Jiménez-Valverde, Lobo & Hortal, 2008).

However, studies of this sort have generally focused on abiotic variables such as latitude, elevation, aspect, soil and climate, which provide relatively crude measures of habitat, and omitted biotic variables such as the known or potential presence of other species of animal (e.g. herbivores, predators, competitors) or plant (e.g. parasites, food plants for herbivorous animal species) (Morin & Gomon, 1993; Ford, Menzel & Odom, 2002). Hence, they probably overestimate the suitability of each location for species occurrence and hence the distribution of suitable locations for the species. Because of this, many authors consider that the models produce descriptions of the 'potential' or 'fundamental' niche and distribution of a species, rather than its 'realized' niche and distribution (Anderson *et al.*, 2002; Anderson, 2003; Illoldi-Rangel *et al.*, 2004; Soberon & Peterson, 2005; Jiménez-Valverde *et al.*, 2008).

By virtue of their inclusion of climatic variables, the models of species distribution using collection data can predict the effects of human-induced global climate change (Peterson *et al.*, 2001, 2002). Such climate changes are predicted to result in a combination of contractions, expansions and geographic shifts in the distributions of species (Peterson *et al.*, 2001, 2002).

(*c*) *Identities and/or numbers of species that occur in particular areas*

There are several reasons why it may be of interest to know or predict which species or how many species occur in a given area. The relationship between the number of species and the area sampled is, for example, one of the oldest and best-documented patterns in community ecology (Chiappy-Jhones *et al.*, 2001). The value of an area for conservation may be higher if it is a 'hotspot' for biodiversity, containing a relatively large number of species, or if it contains threatened species (Myers, 1988, 1990; Prendergast *et al.*, 1993a, b; Reid, 1998; Krupnick & Kress, 2003). The potential or likely impact of human development within an area may depend on whether any threatened species, population or ecological community is present. What factors determine the identities and number of species that occur in an area and the biogeographic patterns of species diversity are also significant ecological questions (Gimaret-Carpentier, Dray & Pascal, 2003).

However, because of the collecting biases described above, it is difficult to use biological collections to provide information of this sort. For example, because of spatial collecting bias, some habitats, and hence the species that occur in them, may be under-sampled. Furthermore, preferential collecting of rarely encountered species may make it difficult to distinguish vagrant and rare species, and failure to collect common species may result in artifactual gaps in their distribution (Goehring *et al.*, 2006). In order accurately to know or predict which species occur in a given area, it is necessary to know the nature and extent of habitat variation within this area and either carry out biological surveys across the range of available habitats or know the patterns of habitat use or occurrence for species that could potentially occur there. Hence, when such information is required, systematic biological surveys are usually carried out (e.g., Haila & Margules, 1996; Fuller *et al.*, 1998; Kingsford, 1999; Willis, Moat & Paton, 2003). Of course, even with collecting biases, assemblages in museums and herbaria provide a starting point for such surveys, but it is clear that protocols for minimizing bias in future acquisitions should become a central part of policy in every museum and herbarium.

Despite these difficulties, a number of attempts have been made to use the information available in biological collections to determine the identities and numbers of species present in particular areas. In most of these studies, the region of interest has been divided into a grid of squares with sides of between 10 and 100 km in length (10 km, Prendergast *et al.*, 1993a; 1 degree, Kress *et al.*, 1998; 1 degree, Peterson, Navarro-Siguenza & Benitez-Diaz, 1998; 3 to 5 min, Schoenfelder, 1999; 1 degree, O'Hara & Poore, 2000; 1/2 degree, Soberón *et al.*, 2000; 1 degree, Crisp *et al.*, 2001; 11 km, Joye *et al.*, 2002; 15 min, Garcillan & Ezcurra, 2003; 10 km, Martinez-Solano & Gonzalez Fernandez, 2003; 0.25 deg, Parnell *et al.*, 2003; 5 min, Gonzalez-Espinosa *et al.*, 2004; 0.5 degree, Rovito *et al.*, 2004; 1 degree, Serrato, Ibarra-Manriquez & Oyama, 2004; 10 km, Stoch, 2004; 0.25 deg, Richardson *et al.*, 2005), and these squares become the areas under consideration. In some cases the areas have been defined politically or geographically (Fisher & Shaffer, 1996; Petersen & Meier, 2003; Petersen, Meier & Nykjaer, 2003; Wang *et al.*, 2003). In all cases attention has been focused on a small number of particular taxonomic groups.

The simplest method to determine the identities and numbers of species in each area has been to calculate which recorded locations, combining all accurate specimen and non-specimen records, lie within each square and to tally the species (Prendergast *et al.*, 1993a; Fisher & Shaffer, 1996; Kress *et al.*, 1998; O'Hara & Poore, 2000; Soberón *et al.*, 2000). When this has been done, however, the resulting map generally resembles a map of human habitation and connecting roads, reflecting once again the tendency for collecting and observations to occur near centres of human activity (Soberón *et al.*, 2000). Not surprisingly, areas where there has been little collecting and/or observing of a particular taxonomic group will have relatively few recorded species, regardless of how many actually occur there, and apparent absences of species from certain areas may or may not be real (Kress *et al.*, 1998; Anderson, 2003). Furthermore, the results of this approach will depend on the adopted spatial scale because the distributions of species are increasingly patchy, rather than continuous, at decreasing spatial scales and, consequently, species richness in particular areas may be overestimated (Hurlbert & Jetz, 2007).

One relatively recent method for determining geographic patterns of species diversity is to overlay the modeled distribution of each species, as described above, across the region of interest and to determine which distributions overlap each area (Feria & Peterson, 2002; Stockwell & Peterson, 2003; Wang *et al.*, 2003; Schmidt *et al.*, 2005). However, this approach should generally overestimate the numbers of species in each area and yield false records of species presence because the modeled distributions will, as discussed above, overestimate the real distributions. Fortunately, new methods for modeling species' distributions are proving increasingly accurate (Elith *et al.*, 2006).

Another method to compensate for the varying levels of collecting/survey effort in each area is based on the observation that the number of recorded species in an area will increase with increasing collecting/observation effort, but at a decreasing rate, until an asymptotic level is reached and on the assumption that this asymptote represents the real number of species present in the area (Myers & Rand, 1969; Colwell & Coddington, 1994; León-Cortés, Soberón-Mainero & Llorente-Bousquets, 1998; Petersen & Meier, 2003). However, as there are generally no direct measures of collecting/observation effort, various surrogate measures have been adopted. One approach has been to take, as the measure of effort, the number of records of plants or animals that are not included in the taxonomic group of interest but would probably have been collected or observed at the same time (Ponder *et al.*, 2001; Anderson, 2003). Another approach has been to take the total number of species collected within a relatively broad taxonomic group over a period of time as a measure of the effort expended on individual species within the group over that period of time (McCarthy, 1998). Another has been to take accumulated time since collecting of a particular taxonomic group began as the measure of accumulating effort (Myers & Rand, 1969). However, none of these seems likely to reflect very well the actual effort expended, and a better approach would be to use visit frequency or time spent at a particular area as the measure of effort, as is possible for some of the recent volunteer- and observation-based animal surveys (Prendergast *et al.*, 1993b).

Another approach is to use mathematical models, similar to those discussed above for individual species, that seek to predict the numbers of species in different areas on the basis of various abiotic variables (Funk & Richardson, 2002; Gonzalez-Espinosa *et al.*, 2004). Using this approach, for example, a number of studies have explored the relationship between species diversity and gradients in rainfall and other climatic variables (Goward & Arsenault, 2000; Hawkins *et al.*, 2003; Gonzalez-Espinosa *et al.*, 2004). However, because of the collecting biases described above, these approaches will generally underestimate the true numbers of species in each area (Petersen & Meier, 2003). Species will tend, for example, to be omitted if they occur in habitats that are undersampled.

Biogeographic patterns in species diversity have, despite such problems, received considerable attention. Some studies have considered the numbers of species in different areas (Wohlgemuth, 1993; Steege *et al.*, 2000; Serrato *et al.*, 2004; Linder, Kurzweil & Johnson, 2005), while others have considered the level of similarity in species composition between different areas (Steege *et al.*, 2000; Ibarra-Manriquez *et al.*, 2002; Garcillan & Ezcurra, 2003). These studies have often considered the role of history and/or environmental factors in explaining the observed patterns (Gimaret-Carpentier *et al.*, 2003; Rovito *et al.*, 2004; Linder *et al.*, 2005; Otte, Esslinger & Litterski, 2005; Parmentier, Stevart & Hardy, 2005; Richardson *et al.*, 2005). Some have focused on geographic patterns in species diversity (Dominguez *et al.*, 1996), others have identified 'hot spots' in terms of species diversity (Garcillan, Ezcurra & Riemann, 2003).

(*d*) *Habitat and behavior*

Associated with each collected specimen, there may be information about either the habitat where the individual was collected or its behaviour at the time, but records of either are rare and biological collections have seldom yielded such information. In the case of collections of a freshwater crayfish from the Australian state of Tasmania, consistent habitat information has been recorded on enough specimen labels to enable the habitats occupied by several species to be described and compared (Hansen & Richardson, 1999). For biological collections to provide information in relation to the behaviour of individuals at the time of collection, the behaviour of an individual must be recorded shortly before it is collected. That this may often be difficult may explain why such information has rarely been associated with collected specimens (Hromada *et al.*, 2003). On the other hand, recent recordings of calls made by individual frogs and collection of each calling individual have shown that such information can reveal variation in calling characteristics between individuals and help to determine taxonomic relations amongst specimens (Brown, Foufopoulos & Richards, 2006a; Brown *et al.*, 2006b). Information that can be obtained from specimens at any time post-collection will be more readily available (see below).

(*e*) *Attributes of individuals*

In addition to information about species identity and collection location, biological collections potentially provide information about various attributes of the collected individuals and about aggregative properties (e.g. mean, variation) of sampled populations with respect to these attributes. This is an area in which specimens in museums and herbaria have demonstrated great value in an astonishing variety of applications. Biological collections permit detailed examination of individuals, sometimes with large numbers of specimens available from a wide range of geographic locations, and this in turn allows for exploration of possible relationships among the attributes of individuals and between these attributes and other factors (Ricklefs, 1980). It may be easier to make morphological measurements and other detailed external observations with specimens that have been collected and are now dead than with live plants or animals. For example, with rare exceptions (e.g. DNA information from non-lethal sampling) it is impossible to make internal examinations of animals unless they are already dead. It may also be easier to access reasonably large numbers of specimens already located in biological collections than to examine fresh material (Ricklefs, 1980). Biological collections may, furthermore, be the only source of historical information about individual attributes (Ponder, 1999).

In this case there will likely still be biases in the available information, but they may be less severe and less common than the biases inherent in considerations of species distribution and population size. Indeed, it may sometimes be possible to assume absences of such biases. For example, the collection methods and protocols, if known, might be such that certain biases should not have occurred, and for internal or inconspicuous external attributes, it may usually be reasonable to assume an absence of bias. A good example would be the collection of insects at light, malaise, or bait traps, where one often can assume collector biases are absent (although numerous other biases such as differential trap attractiveness to individuals or species, bias of location, *etc.* will still be present). Another might be the numbers of seeds per fruit, unless seed number and fruit size are related and there were collecting biases in terms of fruit size. Obviously, eliminating collecting biases may not be easy.

There are a very large number of individual attributes that either have been or could be considered using specimens in biological collections. Externally visible attributes may include sex/reproductive maturity (based on secondary sexual traits) (Takeuchi & Koganezawa, 1994; Olsson, Gullberg & Tegelstrom, 1996), other reproductive traits (e.g. fruit size, seed size) (Carpenter, Read & Jaffre, 2003), various morphological measurements (e.g. mass, body/stem length) (Olsson *et al.*, 1996; Osunkoya, 1996), morphological abnormalities (e.g. missing limbs or digits) (Hoppe, 2000; McCallum & Trauth, 2003), signs of injury or disease (e.g. trauma, tissue damage) (Ristaino, Groves & Parra, 2001;

Antonovics *et al.*, 2003; May & Ristaino, 2004; Weldon *et al.*, 2004), externally visible symbiotic species (Van Dam & Mertens, 1993; Batic & Mayrhofer, 1996; Denys, 2003; Mey, 2003), and plant pollen grains on animals that visit and pollinate plants (Cox, 1983). Internally visible attributes may include sex/reproductive maturity (based on appearance or histology of reproductive organs) (Takeuchi & Koganezawa, 1994), other reproductive traits (e.g. gonadal size, number of eggs or unborn young, number of seeds per fruit) (Emerson, 1997; Holycross & Goldberg, 2001), bone structure (e.g. through radiology) (Davis & Gore, 1947; Hanken & Wassersug, 1986), internal features of exoskeletons (Ehrlich, 1958), abnormalities of organs or tissues (Hayes *et al.*, 2002; Burrowes, Joglar & Green, 2004), and internal symbiotic species (Hromada *et al.*, 2003). Attributes that are discerned through chemical analysis include the nature and extent of contamination with various substances (e.g. mercury, DDT and other pesticides) (Barber, Vijayakumur & Cross, 1972; Miller *et al.*, 1972; Best, 1973; Fleming *et al.*, 1982; Swartz *et al.*, 2003; Newman *et al.*, 2004), chemical composition reflecting that of the atmosphere (Baddeley, Thompson & Lee, 1994), isotope markers (Green & Scharlemann, 2003; Mendes *et al.*, 2007), and genetic constitution (e.g. which alleles of specific genes are present) (Bouzat, Lewin & Paige, 1998; Groombridge *et al.*, 2000; Pergams, Barnes & Nyberg, 2003; Wandeler, Hoeck & Keller, 2007). We shall discuss these various attributes below.

Biological collections have been used, since about the time of Linnaeus, to provide information about the levels of variation within or between populations or species in the attributes of individuals. For example, the observed ranges for particular attributes have often been included as part of species descriptions and have been used to distinguish one species from another (Anstis, 2002). Highly variable traits have sometimes been distinguished from less variable ones. Covariation in traits has sometimes been considered (Osunkoya, 1996).

Over about the same period, biological collections have been used to provide information about internal and external differences between the sexes and between individuals at different stages of development. Descriptions of species have often, for example, included descriptions of differences between males and females and sometimes included separate descriptions of larval, immature and mature individuals or other life stages (Anstis, 2002).

However, in the case of some animal species, this information may only be sufficient to allow for accurate sexing or ageing of individuals on the basis of externally visible attributes after detailed internal and external examination of collected specimens, behavioural observations of individuals, external examination of live individuals, or some combination of these approaches. In the case, for example, of the Australian frog *Limnodynastes peronii* it has been known for some time that there are externally visible differences between reproductively mature males and females (Moore, 1961). However, only through recent comparisons between internal and external examination of specimens of this frog species has it been possible to evaluate the accuracy with which individuals may be sexed and aged (i.e. immature versus adult) on the basis of these characteristics (G.H.Pyke, unpublished data). In this example, furthermore, observations of mating frogs would help to corroborate the adopted methodology for sexing and ageing frogs (G.H.Pyke, unpublished data).

When animal specimens are sexed, aged (e.g. immature versus adult) or measured, the resulting collection may yield information about the frequency distributions of these attributes and hence about patterns of mortality, recruitment, and/or behaviour. Snow (1956), for example, observed that 70% of a sample of blue tits (*Parus caeruleus*), taken at about the beginning of the annual breeding season, were less than one year old. He assumed that the population from which these birds were taken was stable in terms of numbers, and deduced that annual mortality must be about 70%. Ricklefs (1980) observed, for specimens of the bird genus *Turdus*, that the ratio of adults to immatures (i.e. more versus less than one year old) was greatest in both north and south temperate regions, intermediate in the lowland tropics and least in montane localities in the tropics and deduced that population turnover (i.e. annual mortality and recruitment) follows the same geographic trend. Takeuchi and Koganezawa (1994) observed that the proportion of males amongst red fox (*Vulpes vulpes*) specimens was higher amongst young animals (i.e. less than one year old) than among older animals, and deduced that mortality among young males was relatively high. Of course, each of these observed patterns could also have resulted from differences in behaviour, and hence in susceptibility to being collected, between individuals of different age or sex. This approach apparently has not been taken with plants.

Biological collections have provided information in relation to a number of other reproductive traits. In the case of plants, this has included fruit size, seed size, and number of seeds per fruit (Carpenter *et al.*, 2003). For animals, it has included numbers of eggs or unborn young, ovary size, and testis size (Emerson, 1997; Holycross & Goldberg, 2001).

Biological collections have also been used to provide information about growth (Carlson, 1998), allometric relationships (Christian & Garland, 1996; Emerson, 1997; Fitch, 2000; Christiansen, 2002), patterns of variation in external morphology within and between individuals (Ehrlich, 1961; Soulé, 1967; Lens *et al.*, 1999; Lens *et al.*, 2002), and patterns of geographic variation in various attributes (Norman *et al.*, 2002). In cases, for example, where, in addition to information regarding animal body measurements and developmental stage, information regarding age is available (e.g., annual growth rings in birds' feathers-Green & Scharlemann, 2003), it is possible to consider how animals grow and develop through time, and to investigate spatial and temporal variation in growth and development (Green & Scharlemann, 2003).

Information on the origins and spread of disease can also be gleaned from collections. Examination of specimens of the frog *Xenopus laevis* has, for example, indicated that the amphibian chytrid fungal disease *Batrachochytrium dendrobatidis* originated in Africa and spread to other countries through the large-scale distribution of this frog species for pregnancy testing in humans after about 1935 (Weldon *et al.*, 2004). The presence of this disease in specimens of declining Puerto Rican frog species has helped to elucidate the reasons for these declines (Burrowes *et al.*, 2004). Museum specimens of ticks and their hosts in the USA has indicated that the agent responsible for Lyme disease in human beings was present in non-human animal populations well before it was first recorded in *Homo sapiens* (Persing *et al.*, 1990; Marshall *et al.*, 1994). Similarly, the origin and spread of the agent responsible for the human Hantavirus Syndrome within the USA has been detected through examination of museum specimens of *Peromyscus maniculatus* (Yates *et al.*, 2002).

Historic and geographic variation in average morphological traits and in the prevalence of morphological abnormalities within populations has been detected through examination of collections of specimens. The frequency of abnormalities within the frog *Acris crepitans* in Arkansas, USA has, for example, increased over the period 1957 to 2000 (McCallum & Trauth, 2003). Similarly, the background rate of abnormalities in the frog *Rana pipiens* in Minnesota has increased from 0.4% in 1958-1963 to 2.5% in 1996-1997 (Hoppe, 2000). Variation in time and space in eggshell thickness for certain bird species has been determined through examination of museum egg collections (Schwarzbach *et al.*, 2001; Green & Scharlemann, 2003). The average size of collected individuals of American Ginseng (*Panax quinquefolius* L.), a plant that is harvested from the wild, has declined since about 200 years ago when harvesting began (McGraw, 2001).

Biological collections provide a large resource in terms of information about spatial and temporal patterns of morphology, and may enable evolutionary changes to be detected (Tornberg, Monkkonen & Pahkala, 1999; Green & Scharlemann, 2003; May & Ristaino, 2004). For example, based on examination of collected specimens, geographical patterns have been discovered (e.g., Bergmann's rule: Barnett, 1977). For some animal species, the level of bilateral asymmetry, as judged, for example, by the difference between a morphological measurement taken on one side of the body and the same measurement taken on the other side, has been taken as a measure of various genetic and ecological factors, including environmental stress experienced by an animal species, and has been used to consider how such stress may have varied spatially and/or temporally (Soulé, 1967; Lens *et al.*, 1999, 2002; Green & Scharlemann, 2003). Physical abnormalities in frogs, also possible indicators of environmental stress, have been found to vary over space and time (Hoppe, 2000; McCallum & Trauth, 2003; Burrowes *et al.*, 2004). Evolutionary changes have been detected by comparing individuals collected during the periods 1980-1990 and 1960-1970 (Tornberg *et al.*, 1999), recently examined individuals with individuals collected over 100 years ago (Smith *et al.*, 1995), and recently collected and fossil specimens (Hellberg, Balch & Roy, 2001). Seasonal changes in morphology have been considered in a few cases (Yaskin & Emel'chenko, 2003).

Information in relation to the incidence and nature of diseased individuals, and how this has varied spatially and temporally, has also been obtained from collections. For example, the proportion of individuals carrying a particular fungal disease amongst a collection of two plant species, *Silene virginica* and *S. columbiana*, was found to have increased significantly over the past century and been higher in marginal populations, with no apparent bias for or against diseased individuals (Antonovics *et al.*, 2003). Such incidence of disease could be another indication of environmental stress.

Collections have also provided information about the identity and abundance of other symbiotic organisms, and how this has varied over space and time, sometimes providing another indication of pollution or other environmental stress. In apparent response to air pollution, for example, the species of lichens and their abundances on tree specimens from Slovenia varied spatially and temporally (Batic & Mayrhofer, 1996). Similarly, the diatom communities on herbarium macrophytes have been found to reflect water quality (Van Dam & Mertens, 1993). It has also been suggested that a decline in the occurrence of cyanolichens on conifer branches in Europe has resulted from a relatively large increase in acid precipitation there (Goward & Arsenault, 2000).

Collections of animals are also sources of information on diets. Analysis of stomach contents for preserved specimens has enabled identification of individual prey items consumed by these individuals (frogs: Calaby, 1956; snakes: Shine, 1987; fish: Henderson, Dunne & Flannery, 2002; birds: Hromada *et al.*, 2003; Kopij, Nuttall & De Swardt, 2004). In the case of birds, where the stomach and most of the rest of the body have generally been discarded from collected specimens, it has been possible to make inferences about diet and how this may have changed through time and space from analyses of isotope ratios in feathers from the specimens (Chamberlain *et al.*, 2005). Of course, when the entire bird or its stomach-content is retained (e.g. about 12,000 stomach content samples held at the Louisiana State University Museum of Natural History) such indirect inference is not necessary. Isotope ratios obtained from teeth of whale specimens may reflect the diets, habitats and spatial distributions of these animals (Mendes *et al.*, 2007; Rainbow, 2008).

For animal species, collections have, in combination with observational databases, also been used to provide information about the numbers of young per female per breeding attempt, seasonal patterns of breeding and how climate change is affecting animal breeding. Collections and observations of birds' eggs have been used to investigate spatial and temporal variation in clutch size within various bird species, differences among species in average clutch size or its variance, and seasonal timing of breeding (Fisher, 1937; Rodgers, 1990; Green & Scharlemann, 2003). Long-term changes in the seasonal timing of breeding in birds have been linked with changes over similar periods of time in average air temperature and precipitation (Crick *et al.*, 1997; Crick & Sparks, 1999; Scharlemann, 2001).

Furthermore, collections have been used to provide information about chemical contamination and its effects on individual animal morphology and the size of animal populations. The case of DDT contamination, and associated decreases in the thickness of eggshells of certain birds and declines in population sizes for these birds, provides a good and famous example. In this case, examination of collected eggs showed a link between increased contamination by DDT and decreased shell thickness, and other observations linked the decrease in egg shell thickness to increased mortality of young birds and decreased population sizes of adult birds (Ratcliffe, 1967; Hickey & Anderson, 1968; Peakall, 1974). With a ban on the use of DDT, there have been increases in both egg shell thickness and population sizes for these birds, thus further corroborating the links (Grier, 1982). On the other hand, there has been a decrease since the mid-1980s in almost all organochlorines (except polychlorinated biphenyls) in the eggs of the California clapper rail (*Rallus longirostris obsoletus*), without any significant commensurate change in thickness of eggshells (Schwarzbach *et al.*, 2001). Examination of collected specimens has also shown spatial and temporal links between human use of products containing mercury and contamination by mercury in certain fish and the birds that feed on them (Newton, Wyllie & Asher, 1992; Thompson, Furness & Walsh, 1992; Thompson, Becker & Furness, 1993; Thompson, Furness & Lewis, 1993; Monteiro & Furness, 1997).

Collections have supplied materials to be used in chemical analyses to deduce patterns of movement for birds. In some cases, a relationship has been found between the geographic area where an individual bird hatched and grew up and certain isotope ratios in its body, thus allowing estimation of where collected birds originated and hence the nature and extent of their movements (Green & Scharlemann, 2003). The same approach is possible with whales (Mendes *et al.*, 2007) and other relatively mobile animals (Green & Scharlemann, 2003).

Collections of plants have also enabled human-induced changes in the composition of the earth's atmosphere to be detected. Through chemical analysis of plant specimens it has been possible, for example, to follow spatial and/or temporal changes in atmospheric concentration of carbon dioxide and nitrogen (Beerling, Mattey & Chaloner, 1993; Baddeley *et al.*, 1994; Pedicino *et al.*, 2002). Variation in carbon dioxide concentration in the atmosphere has also been linked with variation stomatal density in the leaves of plant specimens (Beerling & Chaloner, 1993). Apparently, however, there have not been similar animal studies.

These studies provide further illustration of how the research focus on biological collections has changed over the years, with environmental issues receiving increased attention in recent times. Prior to about 1960 there were few if any studies of individual attributes of collected specimens that considered an environmental issue, whereas since then, as evidenced by the studies of chemical contamination and environmental stress, many studies have focused on the environment.

IV. DISCUSSION

There is considerable potential for research based on biological collections to contribute to ecological/environmental issues and this potential is being increasingly realised. As the above review illustrates, there is a wide variety of such issues to which biological collections can make significant contributions. Biological collections have already contributed to ecological areas such as population size, distribution of particular species, identities and/or numbers of species that occur in particular areas, habitat and behaviour, and attributes of individuals. They have also been used in the context of environmental issues including pollution, disease and climate change. The large and rapidly growing number of published scientific articles that use biological collections in this regard (Fig. 1) shows how much this use has begun and points to much greater future use in this regard.

However, because biological collections were not originally intended to be used in regard to ecological/environmental issues and have some inherent biases and limitations, these collections are proving more useful in some contexts than in others. Collections have, as discussed above, been most useful in the context of individual attributes and population averages of these attributes. Using this approach to consider biological effects of pollution has, for example, proven very worthwhile. On the other hand, because of the largely opportunistic manner in which collections have generally been assembled, attempts to extract useful information concerning species distributions from biological collections have been less successful. However, there continues to be an effort to find mathematical models that will overcome or are unaffected by these problems (Kadmon *et al.*, 2004; Elith *et al.*, 2006). In addition, programs based on surveys of plants and animals by amateur groups, coupled with voucher specimens and expert identification where identification is doubtful, have been successful in determining patterns of species distribution and how these have been changing (e.g., Biological Records Centre at Monks Wood, U.K.; Prendergast *et al.*, 1993b; Carey & Brown, 1994). Similarly, the plankton samples that have been collected for over 70 years by devices, known as Continuous Plankton Recorders and towed behind boats traversing the North Atlantic Ocean and North Sea, and subsequently identified by appropriate experts, provide an invaluable source of information regarding spatial and temporal patterns of plankton abundance, how these patterns are affected by anthropogenic factors including pollution and climate change, and how these patterns affect populations of fish that feed on the plankton (Batten *et al.*, 2003; Brander, Dickson & Edwards, 2003; Beaugrand, 2005; Rainbow, 2008).

Changes in terms of collections policies and strategies, already occurring at some institutions, could lead to biological collections and their associated research being increasingly seen by the public as relevant and worth the costs involved. Recording geographic locations for collected specimens with a high level of accuracy and geo-referencing of existing specimens should make it possible to determine species' distributions and how these are changing in relation to environmental variables, and to return to precise locations to document trends in biodiversity. Recording information associated with each specimen such as nearby/surrounding habitat, including other individuals observed but not collected, should help to determine the ecological context associated with the specimens. Replacement of haphazard and opportunistic collecting with more rigorous strategies, with identified priorities, for further collecting and adding to existing collections (Alberch, 1993; Miller *et al.*, 2004), should increase the extent to which the public understands and supports the purpose of collecting (Miller *et al.*, 2004). Development of research strategies that give priority to projects that make use of biological collections and include, in addition to taxonomy and systematics, a focus on significant environmental/ecological issues (Alberch, 1993; Drinkrow *et al.*, 1994; Krishtalka & Humphrey, 2000), should help the public to see the relevance of collection-based research. Development of strategies whereby information in relation to collection methods/effort and observations that are not specimen-based are included or associated with the traditional specimen-based information (Willis *et al.*, 2003) should enhance the ecological value of the specimens beyond being simply records of species presence.

There are also some changes to procedures associated with biological collections that could make such collections more useful in the future in the context of ecological/environmental issues. Using modern computer technology, for example, it would be relatively easy to develop relational databases that include details regarding capture methods and effort and information about individual animals that are captured or observed during collecting trips but not actually collected, and that link each specimen with the relevant details (Wohlgemuth, 1993; Knyazhnitskiy *et al.*, 2000). Those who collect specimens could increasingly record standardized information about capture methods, the number of people and/or capture devices, the start and finish times for each capture session, animals that are observed but not captured, animals that are captured but not collected, and so on. At the same time they could record standardized information in relation to the habitat around the point where a plant or animal is encountered and its behaviour at the time (Duellman, 1992; Hromada *et al.*, 2003).

As mentioned above, there are a number of signs that the changes we identify above have already begun to occur, at least in some regions and within some institutions. There is a growing rate of occurrence of publications that significantly use or discuss biological collections in an ecological or environmental context (Fig. 1). Some institutions now have policies and procedures whereby there is extensive accurate geo-coding of locations for existing specimens, locations for new specimens are recorded accurately, habitat and other information associated with specimens is increasingly recorded and included in the computerized databases for the collections of these specimens, and collecting is carried out to contribute to geographic and/or taxonomic gaps (e.g. Missouri Botanical Garden: P. Raven & R. Magill, personal communication; Australian National Herbarium: J. West, personal communication; Australian National Wildlife Collection: L. Joseph, personal communication). Several projects have been established that involve developing countries and, while focusing on taxonomy and the computerization of existing specimen records, include targeted collecting and conservation of biodiversity (Edwards, 2004; Siebert & Smith, 2004; Alberch, 2007). Of course, many of these changes will take a relatively long time to have much effect on the nature and extent of collections. Hopefully, however, through the commencement of such changes now, biological collections will be increasingly seen, by both the scientific community and the public, as relevant and useful in the future.

Institutions that house biological collections should, in our view, pursue a mission of 'understanding the life of the planet to inform its stewardship' (Krishtalka & Humphrey, 2000). Collections would be a major focus for achieving this mission if policies and procedures for acquiring, curating, and studying the materials are revised to suit this goal. Such a mission would lead to careful sampling of nature in aid of understanding how to preserve biodiversity in the face of unprecedented threats, rather than just trying to collect and name as much biodiversity as possible. Adoption of such a mission would also, we hope, lead to the encouragement and support from the public that biological collections need and deserve.

V. CONCLUSIONS

(1) Biological collections and associated research have demonstrated considerable potential to contribute to our understanding of ecological/environmental issues and there is a large and increasing extent to which this potential is being realized. Through such increased association between biological collections and ecological/environmental issues, the public is likely to view such collections with increased appreciation, encouragement and support.
(2) However, achieving this goal is limited by the largely opportunistic way in which biological collections have so far been assembled and will require changes in terms of collection policies, strategies and procedures if these limitations are to be avoided in the future.
(3) Such changes would occur if institutions that house biological collections and associated research programs adopted the mission recommended above. Pursuit of such a mission would result, for example, in collecting and specimen acquisition based on the concept of sampling the biological world with priorities based on ecological/environmental issues as well as taxonomic and geographic considerations.

(4) There are encouraging signs that such changes have already begun to occur.

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