The second Alexandrian tragedy, and the fundamental relationship between biological collections and scientific knowledge

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Introduction

In the next century and beyond, society will understandably query the enigmatic performance of biology in the latter half of the twentieth century. These future generations will ask how natural science collections came to be so severely neglected; and why in consequence, many millions of preserved specimens vanished. They will note that large measures of apathy, allied with a widespread ignorance of the inestimable value of these collections, caused this extirpation of irreplaceable information. This loss of knowledge (which paradoxically occurred in the late twentieth century at the beginning of the Information Age) might be compared to the destruction of the ancient Libraries of Alexandria (which had been entirely lost by AD 638: Gibbon 1778).

As these specimens preserved in natural science collections are lost through neglect and lack of support, unique historical records pass to extinction: these events parallel the biodiversity crisis in destroying unique assemblages of complex information. Is this extirpation of specimens in collections serious? I would argue that it has far reaching consequences. It is not only future, but today's, generations – those concerned about the integrity of the natural sciences – who should probe questionable attitudes, and the accountability of institutions possessing natural science collections, in which specimens are being extirpated.

This paper explores the relationships between biological collections of preserved specimens and humanity's scientific knowledge of the natural world where these specimens were collected. I discuss three interrelated topics: the philosophical basis of the fundamental role of specimens in maintaining biological knowledge; informational relationships of natural science specimens to the biosphere where they originated; and the serious problems which the widespread neglect of collections' values has created. This synopsis partly results from working in central Africa, with exposure to acute problems in collections management and implementing biodiversity studies. Nevertheless, my perspectives are pertinent to similar situations, as the management and future integrity of collections in all countries (including developed nations) is problematic – perhaps more insidiously so.

The dimensions of the crisis

'The most optimistic view is that a third of the world's natural history collections is in extremely poor state, with possibly as many as thirty million specimens per year deteriorating to the extent that they are of no future benefit' (Howie 1993; p. 104). Prevailing support to maintain collections and for taxonomic research on the specimens they contain is pathetic. This crisis impacting on taxonomic resources – losses of collections and extinction of the human skills vital to interpret the origins and affinities of the specimens therein - is of unparalleled seriousness. The integrity of taxonomic resources must be guaranteed, if biological knowledge is to be maintained and improved (Cotterill 1995).

A fair amount has been written about the importance and plight of natural science collections and systematics (Challinor 1983; Edwards 1985; Miller 1985, 1993; Wilson 1985; Danks 1991; Culliota 1992; Duckworth *et al.* 1993; Erlinclioglu 1993; Janzen 1993; Rose *et al.* 1993; Walters 1993; Allman 1994; May 1994; Miller & Scudder 1994; Seymour 1994; Cotterill 1995). Nevertheless, this crisis has yet to be widely recognized and its implications sufficiently understood. The following points require unanimous recognition and response if solutions to the crisis in taxonomy and biology are to be implemented:

1. This pivotal dependence of biological knowledge on collections is insufficiently appreciated within the scientific community. And this neglect proceeds, despite pressing requirements for scientific knowledge of biodiversity. This knowledge is vital to counter the problems facing humanity and the environment; with allied needs in both increasing and potential economic markets.

2. Despite their global importance to science (because of their cosmopolitan representation of the earth's biota), the world's natural science collections are undervalued within the countries where museums and herbaria exist. An urgent need exists to improve scientists' understanding of the fundamental need to collect and preserve specimens.
3. Support for their preservation, and for the human resources to maintain collections and interpret specimens' relationships (their origins and affinities to the natural world), is so inadequate, that their plight seriously threatens the integrity of biological knowledge. The loss of specimens destroys the verifiability of published knowledge and the means to improve it.
4. The need to solve this crisis is of unparalleled urgency. The integrity of taxonomic resources must be guaranteed if biological knowledge is to be maintained and improved. The fundamental value of collections, as the foundations of this knowledge and the sources of its accuracy and reliability, requires urgent and practicable solutions, co-ordinated at an international scale.

Preserved specimens and biological knowledge

Specimen preservation preserves knowledge. Natural science collections have three principal uses. Firstly, their preserved specimens allow scientific theories to be developed with a content amenable to independent review by other scientists. The preservation of these documented specimens allows for the falsification and verification of individual concepts pertaining to the origins and relationships among organisms, as derived from the specimens under scrutiny. Secondly, these specimens support the universal communication of accurate knowledge, whether these concepts are directly derived from specimens, or are subsequently based on the information content of such concepts. Thirdly, specimens can be used for hitherto unforseen investigations: their increasing use as sources (previously unimagined) of preserved DNA is an excellent example. In their fundamental and general context, the preservation of specimens preserves complex information of critical support to scientific knowledge, as this information reduces uncertainties.

In exploring these relationships between biological knowledge and collections of scientific specimens, I base my argument on Popper's philosophy of science: particularly his criteria for objective knowledge (Popper 1972). An objective body of knowledge, such as that known of the biological world, is a body of beliefs produced by information (Dretske 1981, 1985). Dretske's (1981) theory of knowledge accounts for the relationship between preserved specimens and concepts, which building verifiable knowledge, are formed of unequivocal information directly derived from studying these specimens (Cotterill 1995).

The properties of biological knowledge. Generally speaking, information of unspecific and vague meanings can be more easily created and disseminated than knowledge. The differences between information and knowledge have been widely discussed (Ungar 1968; Popper 1972; Batty 1976; Machlup 1980; Meadows 1991; Lehrer 1992). Although the finer details and exact nature of these differences are debated, there is general agreement that knowledge is refined and organised information. The creation of knowledge necessitates the processing and classification of information. Knowledge is built of organised information: its central property being the reduction of uncertainty (Popper 1972; Dretske 1981, 1985; Ayres 1994).

Investigators seek thorough derivation of information from objects of enquiry such that the assembled concepts are accurate, comprehensible, and sufficiently comprehensive. In biology, this carries the costs of objectively investigating a complexity of phenomena and entities. These investigations carry associated costs of managing and communicating collated information in reliable ways. Above all, and this is crucial, derived information needs to be stored for long periods of time. As products of, or in support of research, natural science information can be stored in two different ways. The most thorough and reliable method is to preserve representative examples of subjects of enquiry, from which concepts can be conveniently derived, independent of the natural environments where they typically occur. Another way, and this is normally the complementary approach, is to store observations (concepts of structured information) in media (on paper or electronic format) to facilitate future communication, and to archive this information. These two strategies, by which human investigators derive and preserve information from the natural world, present considerable challenges, in the long-term storage of information. The principal challenge is to maintain the integrity of collected information over the long term. This requires maintaining conceptual accuracies for months, decades and centuries.

As in all the sciences, biological theories rely on an information-based theory of knowledge. This information is verbally communicated among scientists, and transmitted through electronic, written and printed media as packets of information. This communication, whether by verbal, written and electronic means, initially depends on the derivation of accurate concepts, and their maintenance in this state, to minimize equivocation (Dretske 1981). This discourse may sound trivial, but it is pertinent to describe the fundamental basics of how this information is assembled and communicated. And it is taxonomy and systematics, supporting all other biological endeavours, which manages information on complex entities – organisms whose categorization defies cursory observation. This knowledge is absolute, not relative. An information-based account of knowledge traces the absolute character of knowledge to an absolute quantity of information comprising the concept on which it depends (Cotterill 1995).

Specimens are credible sources of concepts. Analogue information is digitally classified in a process which removes noise. Since sensory information is coded into an analogue form and subjected to a digitizing process, specimens are causally responsible for these sensory experiences in the visual dimension of investigators. If we believe the premise that biological knowledge relies on an empirical relationship between specimens and derived observations, then we must accept that all other biological information which does not conform to this axiom is possibly unreliable, and should be recognized as such. (Such a concept may be accurate and true; but it cannot be independently checked.) Cognitive structures acquire their content from their informational origins, a content determined solely by the concept's origin – its informational heritage (Dretske 1981). Each and every one of these concepts must be capable of independent verification. Thus, preserved for subsequent observations, specimens allow independent checking of previously derived concepts. If such a concept is to be scientific, it must be verifiable; the informational origins of the concept must, ultimately, be traceable to a specimen stored in a biological collection (Cotterill 1995).

Because their material constitution is maintained over long periods of time, biological specimens are the best sources available from which biologists can process information to derive concepts of minimum noise and so build accurate knowledge: this process quantifies and minimizes the equivocal content of these concepts. Concepts which specifically account for the origins, interrelationships and identities of organisms are based on representative specimens. The discovery of a previously unrecorded specimen necessitates that a new concept be invented to define this entity's unique properties. Specimens are real bench marks in a complex world, whose properties are a preserved subset of the information contained in the living organism.

Taxonomies of extra-somatical information. The information contained in concepts is linked together in interrelated structures to build taxonomies. Taxonomies are structures of belief which organize information of a high level of intentionality, built of concepts of minimal equivocal content. Taxonomies provide the channels to communicate accurate information from the original sources of all biological investigations; taxonomies, and the methodologies which construct them, are information-processing systems (see Cotterill 1995).

Our existing knowledge of the biosphere, even though it is only partly complete, is built of an immense number of different concepts pertaining to a multifarious variety of topics. All this information cannot be assimilated into the brain of any individual investigator. So in its totality, this knowledge is exosomatic; it exists in isolation from scientists' minds. This objective knowledge, a highly organized body of information, is stored in published form (printed paper and electronic formats). Shared relationships between biological concepts can be traced by universal taxonomies, each of which is organized under discrete but related subjects; examples are the phylogeny of the Archaebacteria, physiology of *Homo sapiens,* comparisons of locomotion in different invertebrates, or the ecology of *Canis lupus.* (And it is no accident that the subject matter of published knowledge, cited for example, in the Zoological Record, is organized into Linnaean taxonomies.) Only if the names of the subjects (identities of organisms, and their shared relationships) of each independent investigation are accounted for by a universal naming system, can such linkages be created and maintained. The structure of biological knowledge is founded in intricate flows of information; the linkages between individual concepts reported in published articles, which describe the properties of natural entities, and the interrelationships among the latter.

Providing for falsification. Popper's invaluable contribution on how scientific investigations should proceed, is centred on his argument that individual concepts and theories of the natural world cannot be absolutely proven, but they can be falsified (Popper 1969). Scientific knowledge is built through the sequential construction and falsification of theories. And through this process, it is the theories which resist repeated and independent attempts at falsification that survive to form a robust body of knowledge.

The findings of an investigation into the properties of a particular population of organisms (or clade of related organisms) must be unambiguously defined in terms of these organisms' identities and affinities to the natural world. If the latter concepts cannot be independently verified, then the results of this study are not falsifiable. They cannot be accurately related to published knowledge about living and extinct life forms. If these concepts of the particular organisms' identities, and their geographical and evolutionary origins, are based on documented specimens, then these concepts remain refutable (*sensu* Popper 1969); available for reinterpretations, counter-arguments and criticism. Such ancillary, and vitally important examinations are only possible if preserved specimens (representing populations of living or extinct organisms) are still available.

A body of knowledge is built of individual concepts (whose properties are described above) – based on communication of information by cognitive means, and the subsequent storage of derived information. In science, these concepts are biologists' observations of the properties and constituents (characters) of organisms, and the complexes in which organisms live, develop and die. Biological knowledge is refined and accumulates as new concepts are derived and compared. Furthermore, peer review is crucial to independently evaluate the informational properties and heritage (the origins of assembled information) of both individual concepts and interrelated suites of concepts. Over the passage of time, many concepts are frequently judged to be partly or utterly incorrect, and are subsequently discarded or modified. It is critical that the necessary conditions for such independent investigations and refutations exist, and that such conditions are maintained.

In the case of organisms, individual concepts are built of information on their different properties, for example, their identities, phylogenetic relationships, anatomies, genetics, geographical origins, behaviours, cellular biochemistry. The taxonomies (which biology has built of all known extinct and extant life forms) constitute the 'cybernetic glue' which holds objective knowledge together. If these foundations are maintained, taxonomic classifications permit universal communication of biological knowledge (Mayr 1968; Cotterill 1995). The integrity of specimens, as the informational sources of these taxonomies, must be maintained if this knowledge is to reliably account for the properties (especially origins and affinities) of these entities into the future. New data need to be compared to published knowledge. Investigators who ignore these requirements pursue a perilous course in collating information of questionable relevance.

Refutations and future uses. It is difficult to predict accurately the future contributions of a particular item of published work in its relations to the greater body of objective knowledge of the natural world. This adds additional imperatives for reliable and accurate communication of the concepts which build the larger assemblage of biological knowledge. A scientific knowledge of the natural world is useless unless it can be applied to solve real world problems, and maintained for future applications by society. To be applicable to the real world, scientific theories must be ultimately grounded in empirical data. Any hypothesis or concept, based on empirical descriptions or theoretical constructs, must be open to independent testing to validate their scientific relevance: their ability to explain the properties of biological systems.

In conclusion: this preservation of biological information, in specimens as material entities, not only allows for the derivation of biological information, but allows concepts to be re-examined. Refutation is vital in the business of science. Preservation of representative specimens, with the latter vouching for the subjects of biological inquiries, is essential if a falsificationist methodology (*sensu* Popper 1969) of scientific investigation is to be accommodated in biology. These derived concepts are hypotheses (identities, classifications, and other properties of organisms) which can be independently tested. Yet, specimens (fundamentally the complex information they store) provide substantially more than their central role in allowing published science to be refuted. Unprecedented investigations of specimens in many different subdisciplines of biology are numerous, with new opportunities still being discovered. The technology to explore this variety of specimens' properties is rapidly improving and future uses of specimens can be only be guessed at today.

Interpreting the biosphere

It is important to review the progress of biology in elucidating the properties of biological systems, and to examine those phenomena requiring future exploration. This perspective will allow us to understand how natural science specimens fit within the broader tableau of scientists' endeavours to interpret the complexities of the biosphere. The scientific basis of studying this biodiversity (my definition follows Noss 1990) has to be clearly defined, widely understood, and reliably perpetuated. Biologists' investigations can proceed in two different ways. Knowledge is gained either from direct observations and experiments, or from constructing theoretical models of these complex systems, and from a combination of both approaches. The scientific relevance of these explanations, that is their success in understanding natural systems, can only be gauged using empirical data gained from direct investigations of natural entities and complexes.

Biology differs from the physical sciences, as it attempts to explain a more complex world (Lewin 1982; Mayr 1982): biology is a historical science. Biologists cannot ignore historical products (O'Hara 1988) – extinct and extant biota evolutionary novelties produced by chaotic systems (Green 1991). Biology is tasked with the exploration and interpretation of this historically derived complexity and communicating this understanding to society. This complexity is an assemblage of inter-nested and interconnected systems, comprising organisms, and their interactions, of millions of different populations.

Organisms, and obviously preserved specimens thereof, are composed of organic materials – the molecules organized by genetic and epigenetic processes. It is information, which has been accumulated over evolutionary timescales, that organizes the assembly of organic macromolecules and tissues (Brooks & Wiley 1988). Through geological time, evolution has accumulated useful information - information which, in a time-honoured manner, has been demonstrated to solve problems by aiding the survival of organisms. Stored in nucleic acids, this genetic information is transferred between organisms via reproductive processes. Ayres (1994) terms this Survival Relevant (SR) Information, and SU (Survival Useful) Information is the subset of SR information directly responsible for an organism's survival, growth and reproduction. SU information directs the construction of organic molecules and macromolecules which form single cells; it codes for developmental and behavioral processes and prescribes the assembly of the tissues and organ systems within multicellular organisms. The differential sorting (through generations of diverging populations) of living organisms, has produced a considerable assemblage of biological diversity, determined at its most fundamental level by the accumulation of an awesome quantity of organised SR information. This biological complexity increases exponentially as we expand our enquiry from cells, to organisms, to interbreeding populations, and to communities of different populations interacting in ecosystems.

Organisms are vehicles, assembled by and containing genetic information, which moving through time and space, process and accumulate energy in complex and diverse ways (Brooks & Wiley 1988). Genetic information has been transmitted and assembled through evolutionary time among diversifying clades of related populations. Biological complexity of the natural world is organized into two hierarchies which separately process information and matter. Complexity results from these disparate processes; the intermeshing, at the level of organisms, of these genealogical and ecological hierarchies (Eldredge 1986, 1992).

The missions of biology

A central mission of biology is to understand the composition and functioning of the living world; to elucidate and interpret the principles and mechanisms of these properties. The mechanisms of energy and information transfer within organisms and cells have been elucidated by *in vivo* and *in vitro* observations, models and experiments. Using these approaches, the intracellular functions and organ systems, common to most life forms, are now comparatively well understood. This is exemplified by the considerable progress achieved in our understanding of how genetic information, at molecular and cellular spatial scales, is maintained, modified and transferred between organisms. Considerable challenges lie in elucidating the finer details of how different components of organisms communicate (especially intricacies of pulsatile secretions and cascade effects of endocrine systems in embryology). Even more daunting, is the quest to understand the emergent properties of complex neural systems, especially the vertebrate brain (Anon. 1994a). An analogous area of research is understanding the determinants and properties of biological complexity and especially the history of this complexification (Kauffman 1992; Szathmary & Maynard Smith 1995) .

The exploration of biological diversity. The dynamic properties of the variety of life are of great interest. Biology seeks to know how such diversity came to be; particularly how this complexity is maintained and how individual components disappear and new entities evolve. This progress in elucidating the mechanisms of life, in exquisite molecular detail, receives much publicity. These successes should be thoughtfully compared against the unexplored dimensions of the diversity of life. Consider, for example, the unexplored domains of bacteria (Woese 1994), the variety of organic chemicals awaiting exploration in insects (Law *et al.* 1992), the diversity of soil fauna (Andre *et al.* 1994), and the intricate and immense variety of interactions between organisms (Dusenbery 1992; Wilson 1992), such as those involving plants (Bruin *et al.* 1995). We need to reconcile with the stark truth that these conceptual and empirical advances in medical and molecular biology have succeeded on a very narrow database, relying on a handful of experimental organisms such as *Escherichia coli*, *Drosophila* spp., *Rattus norvegicus*, *Pan troglodytes* and *Homo sapiens*. Yet, this diversity is so obviously minuscule when compared against that still awaiting exploration (Wilson 1989, 1992).

The very poor understanding of the composition of biological diversity – a central problem in biology – receives increasing attention. Erwin (1983) initiated a review of how little biodiversity (especially at the population level) has been characterized by science. This frontier of ignorance is immense (Andre *et al.* 1994). Paradoxically, its boundaries are shrinking as human activities rapidly destroy biodiversity (Wilson 1992; May 1994). Such ignorance – our poor understanding of biodiversity – appears paradoxical near the close of the twentieth century. Yet this state of affairs escaped deserving review in a commemorative issue of *Nature* (Anon. 1994a), addressing the contemporary state of scientific knowledge.

The exceptional diversity exhibited among these organisms makes an accurate characterization of their individual properties (with respect to each population's identity, origins and affiliations) inherently daunting. The exploration and understanding of this diversity, and the complex assemblages organisms form, is a central challenge to contemporary science. And it stands to reason that we should review and consolidate existing knowledge to identify deficiencies; to focus and support further research (May 1994). At all levels of the hierarchy of life, the properties of biodiversity constitute an immense frontier of ignorance, the dimensions and integral details of which we humans are only beginning to understand.

Systematics and historical ecology can elucidate this complexity. Cladistic maps reconstruct phylogenies, and these allow characters of different organisms (assembled as complex structures of matter) to be objectively compared and their origins understood (Brooks & McLennan 1991, 1993). It needs to be emphasized that an accurate characterization of biological diversity is a considerable and central challenge in biology: to discover and narrate an objective chronicle of biological history (O'Hara 1988); objectively reconstructing phylogenetic relationships among the relevant products of evolution (Cracraft 1992; Faith 1994); with the taxonomic concepts describing the latter organized into accurate classifications (de Querioz & Gauthier 1994). The central importance of an authentic characterization of biodiversity has been terribly neglected. Its relevance to biology is still widely undervalued.

The elucidation of ecological complexity As it applies to the composition of biodiversity, the singular problem in ecological investigations is this pathetically inadequate knowledge of what different organisms occur within the habitats and ecosystems of enquiry. This is not a trivial problem (Harper & Hawkesworth 1994; May 1994). An ATBI (All Taxa Biological Inventory) would considerably reduce this uncertainty, and provide hitherto unavailable insights into the ecosystem which becomes so thoroughly known (Janzen 1993; Yoon 1993; Harper & Hawkesworth 1994); as would a comprehensive charting of the biosphere (Anon. 1994*b*).

Ecology has significantly improved our understanding of the trophic properties of ecosystems. The phenomena of energy and matter transfer are comparatively well understood, especially in well-studied, representative ecosystems (Levin 1992; Holling 1992). The allied disciplines of systematics, palaeontology, historical ecology and biogeography are tackling the challenges of understanding how diversity, especially at the organism level, originated in the biosphere, and how ecological complexes, the communities of interacting organisms, are assembled (Brooks & McLennan 1991; Ricklefs & Schluter 1993*a*). Progress in understanding these phenomena has been limited, partly because it is impossible to emulate the assembly of these historical events. Furthermore, these systems are inherently dynamic and behave chaotically: indeed, these are the central, distinguishing (and unpredictable) properties of ecological systems, which are so inherently difficult for humans to study and understand. Comprehensive investigations of ecological complexes also have to cope with tremendous spatial heterogeneity, even at comparatively small scales (Ricklefs & Schluter 1993*b*). One solution, to account for these and other extraneous influences, is to construct artificial ecosystems under controlled conditions. These rely on intensive screening of candidate organisms to build communities, of interacting populations, under controlled physical conditions (Naeem *et al.* 1994; Cherfas 1994). This approach has provided illuminating insights into ecosystems' properties (Lawton 1994).

It is important to remember that any complex ecological entity is ultimately produced by genetic information: effected through organisms' interactions with their abiotic environments. Organisms process, assemble and redistribute both matter (via mechanical means) and energy (via trophic pathways). It is of central importance to note that it is only organisms which occupy this dual role (*sensu* Eldredge 1986) in processing both matter and information.

Fundamentally, ecologists need to identify the mechanisms by which ecological complexes are produced and maintained (Wiens *et al.* 1993; Jones & Lawton 1995). Investigations of any ecological system must be framed in the historical context in which the system, and its constituents, evolved (Ricklefs & Schluter 1993*a*,*b*). A spectrum of different approaches is needed to understand how ecological communities are assembled, and how they change through time and in different parts of the planet. Requirements centre on evaluating and comparing (in the domains of space and time in which they occur) the micro-processes caused by organisms in ecosystems. Indeed, a great challenge in ecology is to explain clearly how this multitude of micro-processes, operating among organisms at comparatively localized spatial and temporal scales, are produced, and are linked to the comparatively fewer macro-processes generated at larger scales in ecosystems (Holling 1992; Levin 1992; Wiens *et al.* 1993; Jones & Lawton 1995).

The future emphasis. These missions of biology, to push back frontiers of ignorance, to explore biological diversity, and to interpret its complexities, dictates a committed focus on the study of organisms and their attributes (Gans 1985; Lommincki 1988; Wilson 1989, 1992; Wiens *et al.* 1993; Anon. 1994*b*). Such unprecedented attention to elucidating the properties of a huge variety of organisms will forge the foundations on which to understand biological complexity in a representative and object context. The applications of this knowledge to improving the quality of human life (especially the opportunities in biotechnology) are of central importance.

This exploration needs to be encompassing, extending from microscopic scales of biochemical intricacies to the immense domains of extensive ecosystems. And an objective characterization of this biological diversity places unprecedented demands on systematics. Biology's existing knowledge of the true dimensions and actual composition of biodiversity is so pathetic, that it will continue to obfuscate attempts to generate a robust knowledge of biodiversity. The routes which biologists must pursue, to supplant ignorance with objective knowledge, obviously place special emphasis on support and expansion of taxonomic resources – centred on the storage of complex information and biological materials in preserved specimens. It is vital to remember that the interpretation of these specimens' properties is impossible without taxonomic expertise.

Departures from biological reality

Misunderstandings or ignorance?

There appears to be an overpowering urge in humans, especially amongst biologists, to collect new information about the natural world. This exploratory zeal is matched by a paradoxical failure: a chronic neglect to maintain the integrity of collated information. Biologists should recognize this most human of follies – to account for its serious and insidious consequences.

Although it has been emphatically stated that specimens accountably store and maintain complex biological information (e.g. Mayr 1968, 1969; Miller 1985, 1993; Meester 1990; Stirton *et al.* 1990; Goldblatt *et al.* 1992; Peterson & Lanyon 1992; Miller 1993; Miller & Scudder 1994), this axiom appears to be poorly recognized by the majority of biologists. The importance of natural science collections is insufficiently understood. The dependence of biological knowledge on specimens cannot be overemphasized. The misunderstanding of this issue is apparently a primary reason for the neglect of collections. The chronic ignorance of the value of collections, and the scientific disciplines (systematics and taxonomy) directly dependent on them, appears widespread. The fundamental need to collect and preserve specimens of the natural world, especially of living organisms, is generally undervalued. It appears that the scientific integrity of many biologists' investigations collapse when it comes to constructing the taxonomically sound concepts needed to communicate their findings (Cotterill 1995).

Recent perspectives on collections' roles (e.g. Clifford *et al.* 1990) are symptomatic of this naivety of collections' fundamental values, and their true relevance to scientific enquiry. The emphasis (e.g. Arnold 1991) and hyperbole attached to the novel uses of specimens, particularly in molecular research (e.g. Hughes 1992) is made at the expense of their fundamental role in preserving and increasing biological knowledge. Only recently have the serious problems afflicting biological collections received significant attention (1st World Congress in 1992) and been publicized (Duckworth *et al.* 1993; Howie 1993; Morantz 1994; Seymour 1994).

It has been concluded that the process of peer review of biological publications, as judged by the House of Lords Select Committee in the UK, does not always recognize the fundamental role of systematics and biological collections in supporting scientific knowledge (Gee 1992). A more serious problem in biology is not so obvious: some biologists disregard nomenclatural rules of taxonomy, and their importance. Perhaps they might be excused if their attentions were only confined to the narrow specifics of some biochemical functioning of *Escherichia coli* (or some other reliably identified laboratory organism) but even so, accountable identification of specific strains of such laboratory vehicles, particularly of microbes, is essential.

Two representative examples of breakdowns in protocols of communicating scientific information are noteworthy. The recently discovered body of Otze in the southern Alps has recently become the subject of a bizarre ignorance of the taxonomic method. If we are to believe Lubec *et al.* (1994), this well preserved human from the Bronze Age is none other than a new species of *Homo*. I suppose this is no worse than a physicist calling a positron an electron on similar unsubstantiated grounds! Indeed, in science the description of hitherto undiscovered organisms as new taxa is not a flippant affair. Yet, the status of an apparently new bird (a bush shrike from Somalia, of the genus *Laniarius) is* unscientific. The description is not supported by adequate type material, since the only known individual was released under idiosyncratic circumstances ('The Latin name *liberatus* is chosen to emphasize that the bird is described on the basis of a freed individual', Smith *et al.* 1991). Steeped in warm feelings of preservationist intentions, the bird's discoverers were dismissive of the possibility that their 'decision not to collect the bird may cause dismay in museum circles'. This parochial departure from established methods of systematic ornithology has been justly condemned (Peterson & Lanyon 1992; Goodman & Lanyon 1994).

These improprieties in published science incriminate those directly responsible – evidence of the authors' irresponsible naivety of taxonomic protocols. But most seriously, the two blunders described above detract from the scientific standing of the journals which published this scientifically irrelevant information. We are left to ask unpleasant questions of those responsible for maintaining these standards: principally peer reviewers and editors. The scientific community is entitled to query such breakdowns in protocols prescribing accountable routines of scientific investigation, reporting, and publishing. These two examples endorse the need for greater vigilance among editors and scientists to guard against similar departures from the realities of biological research.

An epistemological malaise?

Lack of adherence to scientific methods of investigating complexities of the natural world is inexcusable. Naivety and ignorance of the fundamental basics of biological nomenclature (to which biologists are typically exposed in secondary school biology) is embarrassing. One has to come to terms with a troubling conclusion: this global neglect of systematics' values, apparently allied to the extirpation of taxonomic resources, is symptomatic of a deeper malaise within biology. If the description of *'Homo tirolensis' (incisively* exposed; Anonymous 1995) is indeed indicative of a perfidious failing in biology (an ignorance of elementary taxonomy) then the natural sciences are mired in murky and troubled waters. Much damage may have already been done. Yet, it is difficult to tally, and more especially, quantify which published results have been distorted by shoddy investigations – ignoring elementary basics of taxonomic protocol – particularly through erroneous identifications of the organisms investigated. This problem is surprisingly prevalent in studies of individual species (Meester 1990; Goldblatt *et al.* 1992; Cotterill 1995). As previously argued, if voucher specimens are preserved, these weaknesses in published results are circumvented, with considerable improvement in the applicability and relevance of the collated biological information.

Unless the foundations of biological knowledge are maintained – that is the specimens which account for concepts (for example of those comprising Linnaean taxonomies, cladistic classifications and biogeographical origins of the earth's life forms) are preserved for future referrals – biological knowledge will be reduced to a state of ambivalent statements and an assemblage of theoretical models, which unsubstantiated by empirical knowledge, will be irrelevant to the natural world the science is tasked with elucidating. In continuing to allow the integrity of natural science collections to be jeopardized, those responsible permit the informational foundations (on which biological knowledge exists) to be annihilated. These circumstances draw one to infer that an epistemological infirmity afflicts biology. This is the widespread ignorance of the fundamental protocols by which biological knowledge is created and maintained. Its symptoms are manifested in the neglect of the values of natural science collections, and of systematics and taxonomy. To pursue this argument to an extreme, but logical, conclusion, one may conclude that the widespread reticence of many biologists to sanction support and speak out for taxonomy and collection's preservation and sound management, is equally unprofessional and negligent.

The central importance of collections

Categories of information

To value these historical resources in sufficient representativeness, it is useful to distinguish between two categories of specimens preserved in natural science collections: 'cited' and 'uncited' specimens. Cited specimens are reported on in the primary literature: typical examples are types (the substance and subjects of taxonomic descriptions). This category includes all the vouchers examined in producing any biogeographical and ecological publication, as well as any other specimens examined for other characters, and on which derived information has been published. All cited specimens, by virtue of their historical origins, are irreplaceable. As explained above, preservation of cited specimens anchors the concepts which build biological knowledge.

An unknown but large number of specimens occupy the uncited category (together with their ancillary documented information on labels, data sheets, written registers, electronic databases etc). Although preserved in collections, these specimens have not yet been examined and directly reported on in scientific publications. Some represent undescribed taxa, and unreported geographically associated, or ecological, information. (Although any such single documented specimens *per se* are invaluable, the relevance of the physical circumstances (time and geographical location) in which they were collected are as important.) This information, represented by uncited specimens, is currently difficult for all but the most determined members of the scientific community to access. Until the existence and whereabouts of these uncited specimens, and all other specimens preserved in collections, is advertised, they will remain inaccessible, largely ignored, and consequently under valued. Although uncited-specimens have not been published on, they are no less valuable than cited specimens.

Vouchers of complex information

The role of specimens in building, improving and maintaining biological knowledge centres on their fundamental role in the sustained quantification of complex biological information. As unequivocal samples of the natural world where organisms live and evolve and stored in controlled environments, the central importance of collections is their continued maintenance of complex information in preserved specimens. It needs to be emphasized that cited and uncited specimens are historical records: indubitable representatives of Survival Relevant information (*sensu* Ayres 1994) assembled by evolution. Each and every specimen (assuming it holds adequate documented information on its origin in space and time), is irreplaceable. This role of specimens in science and education was articulated over twenty-five years ago: 'a museum could be considered a vast data bank of three dimensional objects which have locked within them a varying amount of information. Instead of simply storing these data, however, the modern museum undertakes to unlock this information and to interpret it for presentation to the public'. (Galled *et al.* 1968; p. 548).

Accessibility of information

Much of the information held in natural science collections is comparatively inaccessible to the majority of potential investigators. In the era of the Communications Age, both the scientific and socio-economic relevance of the information held in natural science collections has increased considerably, and will continue to do so. A global community of users of this information (in science and industry) exists and is growing. The new-found means to manage the information associated with specimens (the concepts which describe their past and present whereabouts, and summarize their origins and complexity) will increasingly underline their future use. In unprecedented ways, facilitated by the revolution in communications and microcomputers, the biological information preserved in natural science collections is becoming accessible to society (Fortuner 1993; Anon. 1994*b*).

The entirety of information represented by these many millions of specimens is obviously too vast for it all to be completely decoded and thoroughly interpreted. The logical and cost-effective recourse is to preserve the contents of natural science collections into perpetuity. This is vital if an uncountable number of different enquiries (each searching for specific details) are to remain possible (each of these will investigate a portion of the complex information contained in one or more specimens). It is impossible to predict which portions of information (represented by either genetic and morphological characters) in scientific specimens will be the subject of future investigations (Morin & Gomon 1993).

It is unfortunate that human skills and preservation techniques are inadequate respectively to classify and preserve collections with the thoroughness their values decree. Coping with such challenges facing collections' well-being (especially over time spans of decades and centuries) daunts the enthusiasm and support of most biologists and decision-makers. Yet, it is precisely these time spans (and beyond) which the parties, responsible for collections' preservation, need to plan and provide for to preserve biological knowledge. Such shortcomings and challenges provide no excuse for apathy and neglect.

The future of biological collections

The solutions to Alexandria II somewhat parallel those identified for the biodiversity crisis (Harper & Hawkesworth 1994; May 1994; Cotterill 1995). An exhaustive inventory of collections is required, and the results of this global exercise must become available in an electronic format. Electronic registers will supply invaluable information to all investigators seeking to use collections: specifically up-to-date and accurate records of the whereabouts and origins of individual specimens. If collections are to expand beyond their fundamental value (maintaining scientific knowledge of the natural world) specimens' minimum attribute data (origins, identities and present locations) must be published to become rapidly and globally accessible. Recent and rapidly improving technologies (for example to store and process digital images of complex objects) provide considerable opportunities and add new dimensions to the management and study of biological specimens (Alikin & Winfield 1993; Fortuner 1993). Support and facilitation of the electronic documentation of all natural science collections is a most important initiative, and is of extreme urgency.

Underlined by a singular mission in biology to explore and elucidate biological complexity – studying the properties of organisms – new specimens need to be collected and existing material preserved, and the collections thus formed, professionally maintained. The implementation of these activities requires practicable support from the biological community, and from all users of this information, including medicine, biotechnology and conservation agencies. Continued extirpation of collections, and their associated inaccessibility, will impinge on all users of specimen information, and obviously the relevance of biological knowledge to the natural world it attempts to elucidate.

Who is responsible for collections management?

The owners of collections are ultimately accountable for their preservation and management. Some biologists may feel that any commitment to issues of collections' predicaments lies beyond a professional jurisdiction, outside their discipline's primary objective of improving our understanding of the natural world and consolidating this knowledge. Yet, ignoring the problems facing collections, entwined with those destroying taxonomy and systematics (Cotterill 1995), allows the extirpation of biological knowledge – Alexandria II – to proceed unhindered. Such a *laissez faire* attitude is somewhat similar to a politician, acclaimed as an international statesmen, who allows genocide to proceed unhindered in Bosnia, Iraq or central Africa .

The Convention on Biological Diversity (UNEP 1992) does not specifically support requirements for the knowledge derived from collections. This requirement is hardly mentioned in the Global Biodiversity Strategy

(WRI, IUCN & UNEP 1992). As they presently stand, these agendas' endorsements to improve knowledge of biodiversity, so as to support its sustainable use, are practicably impossible to implement. Most importantly, a meaningful portion of funding and support is urgently required to assess, salvage, maintain and develop the world's natural science collections. Until these issues of how biological knowledge is to be improved are addressed, the Biodiversity Convention, and complementary strategies addressing the environment at national, regional and global levels, remain impotent.

There is a pressing requirement for an international body, in a 'watchdog role', to monitor standards of collections' management. It is imperative that both the philosophy and operations of such a corporation are founded on and maintained by a membership of biologists, who are intimately familiar with collections' values. Perhaps an existing body, such as the SPNHC or the World Council of Collections Resources should monitor collections at a global scale, but not if its decision- making is to be constipated and misdirected by bureaucrats perpetuating unscientific and politically-correct policies. Correct staffing of such a body will be the most critical determinant of any success in turning the tide on Alexandria II.

Conclusions

Natural science collections are widely regarded as interesting, but comparatively worthless products of a quaint pastime: 'cabinets of curiosities' in musty museums (Alberch 1993). Such naive perspectives judge collections to be peripheral to the needs of biology, and especially useless to 'mainstream sciences' such as physics and medicine. At very least, this is an unscientific and tragic perspective: unscientific, because it ignores what biology is really about; and tragic, because this viewpoint has precipitated a crisis in the natural sciences; Alexandria II. This global extirpation of biological knowledge is an abysmal state of affairs.

I have argued that the principles and processes in which our scientific knowledge of the biological world is accounted for and substantiated by Dretske's theory of knowledge and Popper's philosophy of science. Information relevant to the survival of organisms *(sensu* Ayres 1994) has accumulated in over 3.8 billion years of evolution, and biology is tasked with interpreting its properties, assembled in organisms and the ecological complexes these form. Biological specimens hold centre stage in this enterprise, because they are original and unadulterated samples of SR information. It is the complex and huge amounts of information assembled in biological systems that distinguishes them from physical systems: and this is the singular imperative for this need to collect and preserve. Permitting objective refutations: specimens eliminate uncertainties and sharpen conceptual accuracies, while fostering unprecedented opportunities for unimagined scientific investigations.

The notion that collections are archives of complex information – unequivocal samples of the natural world – is not new (Galled *et al.* 1968; Danks 1991; Davis & Emery 1993). Biologists face a responsibility (which applies to all subdisciplines) to recognize this explicit role of preserved specimens in their science. Above all, these values of collections ultimately depend on human expertise. Any possibility of interpreting specimens' origins and identities dissolves if taxonomists disappear. Burgeoning losses (in more blunt and accurate terms: unreplaced deaths and retirements) of experienced taxonomists erases exceptional knowledge. The stark consequences of this extinction is the insidious loss of inimitable expertise, uniquely adept at interpreting complex biological information.

It is imperative that any components of any complex biological system (be it one or more different organisms, or parts thereof) investigated in any biological study are correctly classified and universally identified. This requirement is crucial. It applies to any molecular, physiological, behavioral or ecological investigation. Furthermore, because these protocols are abused and so widely ignored in biology, the details and philosophy of these requirements cannot be overemphasized.

The exploration of diversity, at all levels of biological investigation, constitutes the frontier of future opportunity in biology (Mayr 1982; Gans 1985; Gould 1986; Wilson 1989, 1992). An objective knowledge of the biosphere, assembled by pluralistic endeavour through allying different subdisciplines in biology (Wilson 1989) needs to be structured into frameworks built of accurate phylogenies, to support realistic comparisons among biological components (Brooks & McLennan 1991, 1993). Organisms are the focus of attention and referral in biotic exploration. The encompassing need for accurate maps of biological diversity, narrating the historical chronicle of biological evolution *(sensu* O'Hara 1988), is underlined by the mission of systematics to discover and objectively characterize the relevant products of evolution (Cracraft 1992; Faith 1994). It must also be emphasized that accurate taxonomies (*sensu* de Queiroz & Gauthier 1994) are prerequisites to communicate accurately and apply this knowledge, today, tomorrow and into the future.

Poor cognisance of the fundamental prerequisites and foundations of scientific enquiry will continue to erode biological knowledge, and efforts to increase it. Failures to subscribe to these principles will bungle present and future research, and nullify the validity and relevance of published knowledge. A substantive and encompassing revitalization of biology is required. Its objective should underwrite the principals of refutation, especially in the publishing of biological knowledge. Only the responsible parties can directly implement such an exercise: this particularly applies to scientists engaged in peer review, professional biological societies, editors of scientific publications, and those who scrutinize curricula of science education, at both school and tertiary level. The onus is on biologists to maintain and apply the scientific principles on which published knowledge stands or falls.

Biologists who accept the responsibility of reviewing manuscripts must be particularly vigilant. Can identities and classifications be independently checked? Are identities of the organisms, studied, refutable? Where have voucher specimens been deposited for future referrals? Are comparative methodologies founded on phylogenetically accurate taxonomies? The information describing such criteria would necessitate approximately fifty words in a biological publication. Such information forms the central crux of taxonomic revisions; in which it is typically more detailed and consumes more publishing space.

At a more encompassing scale, biologists should seriously evaluate the ramifications of issues at national or global scales: examples being the pathetic funding for collections' management; failures to support taxonomists' employment; cutting of posts; and similar victims of proverbial funding cuts. Biologists need to evaluate such impacts on the knowledge we strive to improve and maintain. We should especially consider the deeper ramifications of potentially damaging issues. As scientific professionals, biologists need to object to circumstances which will destroy or are destroying any facet of the irrevocable foundations of biological knowledge, and the resources to build on and interpret such knowledge. This especially applies to policy changes and decisions in corporate management – frequently driven by unscientific and myopic priorities. Scientists' responses should lucidly articulate their concerns; to spell out consequences and implications in plain language; and place unscientific follies of ignorant or myopic decision-makers into their deserving context.

Shortcomings and failures need to be displayed for what they really are. None of us like to hear probing and unpleasant questions asked of our own scientific integrity. Nonetheless, this process will generate victims: rejected manuscripts, failed theses, punctured egos of those whose work (e.g. Smith *et al.* 1991; Lubec *et al.* 1994) bears the brunt of acerbic editorials (e.g. Anon. 1995) or rebuttals (e.g. Peterson & Lanyon 1992). But biology, and especially the knowledge it publishes, will be stronger for such criticism. A fervent, imperious purge would be counterproductive. Instead, those privy to specifics of a particular scientific enquiry and findings – reviewing particular studies in which details and design fail to meet the demands of sufficient scientific rigour – need to exercise judiciously objective criticism under appropriate circumstances. Only biologists can maintain the quality, and thus the relevance of biology. Indeed, this is a primary responsibility of the professional scientist; biologists directly control how biological information is interpreted and published. In all sciences, the price of the objective quality of the knowledge they build is eternal vigilance. The need for such qualities, namely an objective relevance, of biological knowledge has never been greater.

I am most grateful to Don Broadley and Doug Lang for their comments on the manuscript.

References

ALBERCH, P. 1993. Museums, collections and biodiversity inventories. *Trends in Ecology and Evolution*, **8**, 372–375.

ALIKIN, B. & WINFIELD, P. 1993. Cataloguing biodiversity: new approaches to old problems. *Biologist*, **40**, 179–183.

ALLMAN, W. D. 1994. The value of natural history collections. *Curator*, **37**, 83–89.

ANDRE, H. M. M., NOTI, I. & LEBRUN, P. 1994. The soil fauna: the other last biotic frontier. *Biodiversity and Conservation*, **3**, 45-56.

ANON. 1994*a*. Frontiers of ignorance. *Nature*, **372**, 1–36.

——— 1994*b*. *Systematics Agenda 2000: Charting the Biosphere*. Technical Report. Department of Ornithology, American Museum of Natural History, New York.

——— 1995. Naming people lightly. *Nature*, **373**, 176.

ARNOLD, E. N. 1991. Biological messages in a bottle. *New Scientist*, **1783**, 25.

AYRES, R. U. 1994. *Information, Entropy, and Progress. A new evolutionary paradigm*. American

Institute of Physics, New York .

BATTY, C. D. 1976. *Knowledge and its organization.* University of Maryland Press, Maryland.

BROOKS, D. R. & MCLENNAN, D. A. 1991. *Phylogeny, ecology, and behaviour: A research program for comparative biology*. Chicago University Press, Chicago.

BROOKS, D. R. & MCLENNAN, D. A. 1993. Historical ecology: examining phylogenetic components of community ecology. *In:* RICKLEFS, R. E. & SCHLUTER, D. (eds) *Species Diversity in Ecological Communities*. Chicago University Press, Chicago, 267–280.

——— & WILEY, E. O. 1988. *Evolution as Entropy. Toward a unified theory of biology.* (2nd edn). Chicago University Press, Chicago.

BRUIN, J., SABELIS, M. W. & DICKE, D. 1995. Do plants tap SOS signals from their infested neighbours? *Trends in Ecology and Evolution*, **10**, 167–170.

CHALLINOR, D. 1983. Preservation for all posterity. *New Scientist*, **99**, 959.

CHERFAS, J. 1994. How many species do we need? *New Scientist*, **1937**, 36–40.

CLIFFORD, H. T., ROGERS, R. W. & DETTMAN, M. E. 1990. Where now for taxonomy? *Nature*, **346**, 602.

COTTERILL, F. P. D. 1995. Systematics, biological knowledge and environmental conservation. *Biodiversity and Conservation*, **4**, 183–205.

CRACRAFT, J. 1992. The species of the birds-of-paradise (Paradisaeidae): applying the phylogenetic species concept to a complex pattern of diversification. *Cladistics*, **8**, 1–43.

CULLIOTA, E. 1992. Museums cut research in hard times. *Science*, **256**, 1268–1271.

DANKS, H. V. 1991. Museum collections: fundamental values and modern problems. *Collection Forum*, **7**, 95-111.

DAVIS, G. & EMERY, A. 1993. Resolutions from the International Symposium and World Congress on the Preservation and Conservation of Natural History Collections. *In:* PALACIOS, F. MARTINEZ, C. & THOMAS, B. (eds) *International Symposium and First World Congress on the Preservation and Conservation of Natural History Collections* (Vol. I). Direccion General de Bellas Artes y Archivos, Madrid, 23–39.

DE QUERIOZ, K. & GAUTIER, J. 1994. Toward a phylogenetic system of biological nomenclature. *Trends in Ecology and Evolution*, **9**, 27–31.

DRETSKE, F. L. 1981. *Knowledge and the Flow of Information.* Blackwell Scientific, Oxford.

——— 1985. Precis of 'Knowledge and the Flow of Information'. *In:* KORNBLITH, H. (ed.) *Naturalising Epistemology.* MIT Press, Cambridge, 169–187.

DUCKWORTH, W. D., GENOWAYS, H. H. & ROSE, H. L. 1993. *Preserving Natural science Collections: Chronicle of our environmental heritage.* National Institute for Conservation of Cultural Property, Washington DC.

DUSENBERY, D. B. 1992. *Sensory Ecology. How organisms acquire and respond to information.* W. H. Freeman, San Francisco.

EDWARDS, R. Y. 1985. Research: A museum cornerstone. *In:* MILLER, E. H. (ed.) *Museum Collections: Their roles and future in biological research.* British Columbia Provincial Museum. Occasional Papers Series, Victoria, 1–11.

ELDREDGE, N. 1986. Information, economics, and evolution. *Annual Review of Ecology and Systematics*, **17**, 351–369.

——— 1992. Where the twain meet: causal intersections between the genealogical and ecological realms. *In:* ELDREDGE, N. (ed.) *Systematics, Ecology, and the Biodiversity Crisis.* Columbia University Press, New York, 1–14.

ERLINCLIOGLU, Y. Z. 1993. The failure of the Natural History Museum. *Journal of Natural History*, **27**, 989–992.

ERWIN, T. L. 1983. Tropical forest canopies: the last biotic frontier. *Bulletin of the Entomology Society of America*, **29**, 14–19.

FAITH, D. P. 1994. Phylogenetic pattern and the quantification of organismal biodiversity. *Philosophical Transactions of the Royal Society of London*, **B345**, 45–58.

FORTUNER, R. ed. 1993. *Advances in Computer Methods for Systematic Biology: artificial intelligence, databases, computer vision.* John Hopkins University Press, London.

GALLED, S. R., OLIVER, J. A., ROBERTS, H. R., FRIEDMANN, H & SQUIRES, D. F. 1968. Museums today: museums provide links in the modern communications chain. *Science* **161**, 548–551.

GANS, C. 1985. 'In praise of diversity.' A keynote address. *In:* GRIGG, G., SINE, R. & EHMANN, H. (eds) *Biology of Australian Frogs and Reptiles*, Royal Society New South Wales, xi–xvi.

GEE, H. 1992. Peers slam peer review. *Nature*, **355**, 488.

GIBBON, E. 1778. *Decline and Fall of the Roman Empire.* Everyman, London.

GOLDBLATT, P., HOCH, P. C. & MCCOOK, L. M. 1992. Documenting scientific data: the need for voucher specimens. *Annals of the Missouri Botanical Garden.* **79**, 969–970.

GOODMAN, S. M. & LANYON, S. M. 1994. Scientific collecting. *Conservation Biology*, **8**, 314–315.

GOULD, S. J. 1986. Evolution and the triumph of homology or why history matters. *American Science*, **74**, 60–69.

GREEN, D. M. 1991. Chaos, fractals and nonlinear dynamics in evolution and ecology. *Trends in Ecology and Evolution*, **6**, 333–337.

HARPER, J. L. & HAWKESWORTH, D. L. 1994. Biodiversity: measurement and estimation. *Philosophical Transactions of the Royal Society of London*, **B345**, 5–12.

HOLLING, C. S. 1992. Cross-scale morphology, geometry, and dynamics of ecosystems. *Ecology Monographs*, **62**, 447–502.

HOWIE, F. M. 1993. Natural science collections: extent and scope of preservation problems. *In:* ROSE, C. L., WILLIAMS, S. L. & GISBERT, J. (eds) *International Symposium and First World Congress on the Preservation and Conservation of Natural History Collections.* (Vol. III) Direccion General de Bellas

Artes y Archivos, Madrid, 97–110.
HUGHES, A. L. 1992. Avian species described on the basis of DNA only. *Trends in Ecology and Evolution*, **7**, 2–3.
JANZEN, D. H. 1993. Taxonomy: universal and essential infrastructure for development and management of tropical wildland biodiversity. *In:* Sandlund, O. T. & Schei, P. J. (eds) *Proceedings of the Norway/UNEP Expert Conference on Biodiversity*, Trondheim, May 1993. NINA, Trondheim, 100–113.
JONES, C. G. & LAWTON, J. H. (eds) 1995. *Linking Species and Ecosystems*. Chapman & Hall, New York.
KAUFFMAN, S. A. 1992. *The Origins of Order*. Oxford University Press, Oxford.
LAW, J. H., REBEIRO, J. M. C. & WELLS, M. A. 1992. Biochemical insights derived from insect diversity. *Annual Reviews Biochemistry*, **61**, 87–111.
LAWTON, J. H. 1994. What do species do in ecosystems? *Oikos*, **71**, 367–374.
LEHRER, K. 1992. *Theory of Knowledge*. Routledge, London.
LEVIN, S. A. 1992. The problem of pattern and scale in ecology. *Ecology*, **73**, 1943–1967.
LEWIN, R. 1982. Biology is not postage stamp collecting. *Science*, **216**, 718–720.
LOMMINCKI, A. 1988. *Population Ecology of Individuals*. Princeton University Press, Princeton.
LUBEC, G., WENINGER, M. & ANDERSON, S. R. 1994. *FASEB Journal*, **8**, 1166–1169.
MACHLUP, F. 1980. *Knowledge and knowledge production 1*. Princeton University Press, Princeton.
MAY, R. M. 1994. Conceptual aspects of the quantification of the extent of biological diversity. *Philosophical Transactions of the Royal Society of London*, **B345**, 13–20.
MAYR, E. 1968. The role of systematics in biology. *Science*, **159**, 595-99.
——— 1969. *Principles of Systematic Taxonomy*. McGraw-Hill, New York.
——— 1982. *The Growth of Biological Thought: Diversity, Evolution and Inheritance*. Harvard University Press, Cambridge.
MEADOWS, A. J. (ed.) 1991. *Knowledge and Communication. Essays on the Information Chain*. Library Association Publishing, London.
MEESTER, J. 1990. The importance of retaining voucher specimens. *In:* HERHOLDT, E. M. (ed.) *Natural History Collections: their management and value*. Transvaal Museum Special Publication No. 1. Transvaal Museum, Pretoria, 123–127.
MILLER, E. H. (ed.) 1985. *Museum Collections: Their roles and future in biological research*. British Columbia Provincial Museum, Occasional Papers, Victoria, **25**.
——— 1993. Biodiversity research in museums: a return to basics. *In:* FENGER, M. A., MILLER, E. H. JOHNSON, J. F. & WILLIAMS, E. J. R. (eds). *Our Living Legacy: Proceedings of a Symposium on Biological Diversity*. Royal British Columbian Museum, Victoria, 141–173.
——— & SCUDDER, G. G. E. 1994. A rose by any other name. *In:* HARDING, L. E. & MCCULLUM, E. (eds) *Biodiversity in British Columbia: Our changing environment*. Victoria: Environment Canada, 29–43.
MORANTZ, A. 1994. Tomb of the unknown creature. *Equinox /Canada*, **76**, 5.
MORIN, N. R. & GOMON, J. 1993. Data banking and the role of natural history collections. *Annals of the Missouri Botanical Garden*, **80**, 31722.
NAEEM, S., THOMPSON, L. J., LAWLER, S. P., LAWTON, J. H. & ROODFIN, R. M. 1994. Declining biodiversity can alter the performance of ecosystems. *Nature*, **368**, 734–737.
NOSS, R. F. 1990. Indicators for monitoring biodiversity. *Conservation Biology*, **4**, 355–64.
O'HARA, R. J. 1988. Homage to Clio, or, toward an historical philosophy for evolutionary biology. *Systematic Zoology*, **37**, 142–55.
PETERSON, A. T. & LANYON, S. M. 1992. New bird species, DNA studies and type specimens. *Trends in Ecology and Evolution*, **7**, 167–8.
POPPER, K. 1969. *Conjectures and Refutations*. Routledge and Kegan Paul, London.
——— 1972. *Objective Knowledge*. Oxford University Press, Oxford.
RICKLEFS, R. E. & SCHLUTER, D. (eds) 1993*a*. *Species Diversity in Ecological Communities*. Chicago University Press, Chicago.
——— & ——— 1993*b*. Species diversity: regional and historical influences. *In:* RICKLEFS, R. E. & SCHLUTER, D. (eds) *Species Diversity in Ecological Communities*. Chicago University Press, Chicago, 350–363.
ROSE, C. L., WILLIAMS, S. L. & GISBERT, J. (eds) 1993. *Current Issues, Initiatives, and Future Directions for the Preservation and Conservation of Natural History Collections*. Direccion General de Bellas Artes y Archivos, Madrid.
SZATHMARY, E. & MAYNARD SMITH, J. 1995. The evolutionary transitions. *Nature*, **374**, 227–232.
SEYMOUR, J. 1994. No way to treat a national treasure. *New Scientist*, **1916**, 32–35.
SMITH, E. F. G., ARCTANDER, P., FJELDSA, J. & AMAR, O. R. 1991. A new species of shrike (Laniidae: *Laniarius)* from Somalia, verified by DNA sequence data from the only known individual. *Ibis*, **133**, 227–235.
STIRTON, C. H., BOULDS, L., MACFARLANE, T. D., SINGH, N. P. & NICHOLAS, A. 1990. In defence of taxonomy, *Nature*, **347**, 223–224.
UNEP 1992. *The Convention on Biological Diversity*. UNEP, Nairobi.
UNGAR, P. 1968. An analysis of factual knowledge. *Journal of Philosophy*, **65**, 157–70.
WALTERS, S. M. 1993. Herbaria in the 21st century: why should they survive? *Webbia*, **48**, 673–682.
WIENS, J. A., STENSETH, N. C., VAN HORNE, B. & INS, H. A. 1993. Ecological mechanisms and landscape ecology. *Oikos*, **66**, 369-380.
WILSON, E. 0. 1985. Time to revive systematics. *Science*, **230**, 1227.
——— 1989. The coming pluralization of biology and the stewardship of systematics. *Bioscience*, **39**, 242–245.
——— 1992. *The Diversity of Life*. The Belknap Press

of Harvard University, Cambridge.
WOESE, C. R. 1994. There must be a prokaryote somewhere: microbiology's search for itself. *Microbiology Reviews*, **58**, 1–9.
WRI, IUCN & UNEP 1992. *Global Biodiversity Strategy: Guidelines for Action to Save, Study and Use the Earth's Biotic Wealth Sustainably and Equitably*. World Resources Institute, Washington DC.
YOON, C. K. 1993. Counting creatures great and small. *Science* , **260**, 620–622.

The Value and Valuation of Natural Science Collections

Proceedings of the International Conference, Manchester, 1995

EDITED BY

J. R. NUDDS and C. W. PETTITT

THE MANCHESTER MUSEUM

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THE Systematics ASSOCIATION

1997
Published by
the Geological Society
London