The contemporary view of biodiversity: bad science and bad policy

Andrew Beattie

Department of Biological Sciences, Macquarie University, NSW 2109, Australia

> *"I make no apologies for putting microorganisms on a pedestal above all other living things, for if the last blue whale choked to death on the last panda, it would be disastrous but not the end of the world. But if we accidentally poisoned the last two species of ammonia-oxidisers, that would be another matter. It could be happening now and we wouldn't even know…"* (*Professor Tom Curtis, July 2006, Nature Reviews Microbiology*)
>
> *"Setting up dichotomies of economic growth versus the protection of nature is a dead-end for conservation".* (*Michelle Marvier, June 2012, Frontiers in Ecology and the Environment*).

ABSTRACT

Biodiversity conservation science and policy largely ignores the majority of species: the microbes and invertebrates. This biodiversity contains most genetic, metabolic and chemical diversity on Earth and underpins a wide variety of ecosystem services, an unexpected diversity of major industries and, ironically, conventional conservation. Its exclusion, often explained by inadequate scientific technologies, is no longer tenable. On the other hand, its inclusion in biodiversity science and policy will: 1) enhance understanding of the processes and mechanics of ecosystem services, 2) place biodiversity at the core of all economies, 3) realise a vast array of new biological resources, 4) extend responsibility for conservation into industrial sectors that depend on biodiversity, 5) generate a new interest in the workings of the planet through the 'Attenborough Effect'.

Key words: biodiversity, economics, bioresources, microbes, invertebrates, agriculture, biodiversity policy, Attenborough Effect

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Introduction

In 1992, the Rio Convention on Biological Diversity announced: *Biological Diversity means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.* What remained unclear was the fact that most species are either invertebrate or microbial and together they harbour the majority of genetic, metabolic and chemical diversity on Earth (Demain 2000; Keeling *et al.* 2005; Achtman *et al.* 2008; Mora *et al.* 2011). At present it is not possible to say with certainty what proportion of the total this diversity represents, but there is plenty of evidence that it is in excess of 90% (e.g., Ponder and Lunney, 1999). Conservation science largely ignores this majority, which is bad science. It follows, therefore, that conservation policies based on this science are bad policies.

The situation for biodiversity conservation in Australia and overseas is grim; current policies rarely work. This is because almost everyone involved has adopted the proposition that biodiversity is *de facto* subsets of flowering plant and vertebrate groups. In Australia, for example, much biodiversity science and policy is directed at endangered species, remnant native vegetation, and the management of invasives (see Recher this volume). Thus, farmers experience biodiversity conservation as legislation requiring particular remedial actions that are generally costly in terms of time, labour and money. A frequent perception is that biodiversity conservation is intrusion by outsiders – government departments, environmental organisations and academics. A fatal consequence of this bad science and policy is that few in the agricultural industries recognise that this biodiversity populates the human food chain; that their income is biodiversity-based or even that farmers are in every sense biodiversity managers. Most are exposed to the view that biodiversity refers only to selected flowering plants and vertebrates in their locality and not to the huge numbers of species, mostly but not exclusively in the soil, that enable their crops and forage plants to grow; that drive yields and profits. The skewed scientific emphasis means also that the study of invasive species is critically biased away from microbes and invertebrates (Pyšek *et al.* 2008; Jeschke *et al.* 2010). The invasive fungal plant pathogen, *Puccinia psidii*, that now threatens an alarming variety of native Australian plant species, is still known only as a species 'complex' (Carnegie and Cooper 2011). Overall, the greatest number of projected species extinctions are invertebrate (Collen *et al.* 2012). This is widely ignored even in the context of the complex invertebrate and microbial food webs that maintain the target iconic species of popular conservation. How has all this come about?

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Imagine a ploughed field bordered by forest. The current view of biodiversity is that the forest, be it tropical or temperate, abounds with biodiversity but the ploughed field has little or even none. In fact, while the forest may well harbour many species, the field may harbour just as many. The trouble is that in the field they are mostly invertebrate and microbial and hidden in the soil. Yet it is the metabolic activities of these many thousands of species in the soil that enable the production of what the farmer wants, be it a crop or forage. To be sure, the soil biodiversity is largely different to that of the forest, but it is important biodiversity and to ignore its conservation is folly, as we shall see later. This situation is not confined to agriculture as there are many parallels with the forestry and fishing industries.

The situation is exemplified by a recent statement in a front-line scientific journal: *"Thus, farming will continue to be the major cause of habitat and biodiversity loss"* (Ramankutty and Rhemtulla, 2012). This is of course true in the conventional sense that land clearing for food production eliminates native vegetation and the natural habitat of the kinds of animals that conservationists focus on. What it ignores, ironically, is that modern farming remains a biodiversity-based industry, but its methods threaten the biodiversity of the soils upon which it depends.

This paper explores the disastrous situation in which biodiversity is widely regarded as amounting to a relatively few conspicuous species so that the conservation of biodiversity is thought of as a problem exclusively for conservationists (e.g., Redford *et al.* 2012); a situation that recent history shows creates many unnecessary enemies

Some numbers

Science knows relatively little about the species with which we share the planet: The latest estimates of the numbers of species on Earth range between 7 and 10 million with an estimated 86% of terrestrial species and 91% of ocean species still awaiting discovery and description, and these estimates ignore the Bacteria and Archaea (Keeling *et al.* 2005; Mora *et al.* 2011). Basset *et al.* (2012) estimate that there are about 6.1 million arthropod species alone. Most animal and plant species are protozoan or algal respectively; very small and easy to ignore. Add to these the invertebrates and microbes, most of which are also either tiny or microscopic, and you have a bewildering number of species and astronomical numbers of individual organisms. The most common species on Earth may be the marine bacterium *Pelagibacter ubique* (Yooseph *et al.* 2010) that has profound effects on global nutrient cycles, but because it is microscopic and planktonic its name is unknown to the public. The Bacteria and Archaea provide an enormous challenge for biologists as defining species is often so difficult that the genome may be the most practical unit. As microbial diversity is properly assessed, planetary biodiversity will jump by orders of magnitude (Achtman *et al.* 2008).

The most common reason offered for ignoring this biodiversity is that there are simply too many unknown species and we do not have the technologies available to sample and process them. This is no longer true. Invertebrates of many kinds can be included in surveys as a result of the development of a variety of systems designed for this purpose (e.g., Oliver and Beattie 1996; Colwell 1997; Oliver *et al.* 2000; Kean *et al.* 2012; Costello *et al.* 2013). The same can be said of the existing molecular systems and those in the pipeline for processing microscopic invertebrates and the Bacteria, Archaea, and fungi (e.g., Hayden 2012a,b; Boyer *et al.* 2012; Lozupone *et al.* 2012; Gewin 2012). Given the available high-speed methods, why don't we assess and compare, for example, natural and agricultural environments on the basis of the diversity of their microbial drivers such as methanogens, nitrogen-fixers or cellulose degraders?

Production Biodiversity

Ecosystem services such as the regulation of soil fertility, structure and moisture content underpin all primary production industries, but what is the role of biodiversity in these services (Ehrlich, this volume)? What groups perform which functions and are they abundant or should they be managed or conserved? Do modern agricultural methods encourage or destroy them? We know, for example, that the addition of excessive nitrogenous fertilizer significantly reduces the activities of beneficial microbes (Carreiro *et al.* 2000) – information important for both agriculture and conservation.

Arthropods in general and insects in particular have been evaluated for their services to crop pollination, the biological control of pests, dung burial, and their role in food chains of vertebrate species around which there are major recreational hunting and fishing industries (Isaacs *et al.* 2009; Losey and Vaughan 2006). The estimates all run into many billions of dollars annually for the USA alone and explicitly include groups not normally regarded as being of positive economic value, such as beetles and flies.

Knowledge of the values of wild arthropod pollinators is remarkably good. While there has been much emphasis on the role of the honeybee in crop yields, its decline has turned attention not only to a wide array of native bee pollinators (the commercially favoured honeybee is feral outside of southern and southeastern Asia), but also to a wide range of pollen vectors including flies, wasps, beetles, bees, and butterflies. Production from 87 leading global food crops is dependent on animal (mostly insect) pollination (Klein *et al.* 2007; Kennedy *et al.* 2013).

One of the most important lessons to be learned is that the interactions between crops and wild pollinators, between crops and native vegetation, are two-way streets: worldwide reviews of crop pollination show significant increases in yields that result from the activities of wild pollinators of many kinds, not just bees, both in Australia (Blanche *et al.* 2005, 2006; Heard *et al.* 1990) and worldwide (Ricketts *et al.* 2008; Garibaldi *et al.* 2010; 2011). Further, global dependence on wild pollinators is increasing (Aizen *et al.* 2008). While relatively few crops rely exclusively on wild pollinators, yield increases in nearly all of these crops are important economically (Klein *et al.* 2007) This has led to strong advocacy for the retention of native vegetation in croplands for the provision of native pollinator habitat (Garibaldi *et al.* 2010, 2011).

Benefits in the reverse direction are less well understood, but research shows that, for example, the pollen and nectar resources offered by crops sustain or even increase the densities of arthropod species that are wild pollinators (Westphal *et al.* 2003). Further, agricultural land has multiple benefits for wild bees and wasps (Steffan-Dewenter 2003; Mandelik *et al.* 2012). This is an area of research that needs more attention.

Almost all biological control agents are either microbial or invertebrate, which means that the major alternative to chemical pesticides resides within this vast biodiversity (Bellows and Fisher 1999; Biello 2010). A wide array of these organisms have been deployed for centuries (e.g., Beattie 1985), are already cultured in vast numbers for application to crops and orchards (e.g., www.bugsforbugs.com.au) or are in the trial phase either as sole agents or for inclusion in integrated pest management schemes (www.journals.elsevier.com/biological-control/.) Arthropod biodiversity is a vast resource for pest control as it includes useful groups with very large numbers of species, such as mites and wasps (Bellows and Fisher 1999). The dung control industry, well established in many countries, is a good example of the use of invertebrate biodiversity, in this case that of beetles, on an industrial scale (Nichols *et al.* 2008). Fungal biodiversity is the source of a major pest control industry (e.g., Remadevi *et al.* 2010). The venoms of spiders have emerged as potential insecticides, being hyperstable mini-proteins that target novel sites in specific pest insects. There are perhaps 100,000 spider species worldwide, a large potential resource (Windley *et al.* 2012).

Ants are biological control agents, but managing them can be difficult (e.g., Majer, 1986; Rico-Gray and Oliveira 2007). Along with termites, ants provide other important services for which they are less well known, such as soil bioturbation and increasing water penetration and soil nitrogen in dry climate crops (Evans *et al.* 2011). A huge array of invertebrates is vital for soil fertility in tropical (Lavelle *et al.* 1994; Lawton *et al.* 1996), arid (Whitford 1996) and temperate (De Deyn *et al.* 2003, Stinner and House 1990) ecosystems, and substrate quality in littoral (Lohrer *et al.* 2004) zones. While the functions of earthworms are well known in soil ecosystems, the beneficial activities of nematode worms, mites, springtails, beetles, termites, millipedes, centipedes, spiders and ants - many thousands of species – are little appreciated. Biogeochemical cycles generated by the activities of invertebrates in littoral substrates (muds and sands) are poorly understood, but the importance of sea urchins, for example, have been clearly demonstrated (Lohrer 2004). Many marine substrates are inhabited by phyla little known even to biologists; what they contribute is anyone's guess.

Knowledge of microbial contributions to primary production industries is patchy, but the importance of some are so well understood their names should be better known: *Nitrosomonas, Nitrobacter, Pseudomonas* and *Azotobacter* are among the bacterial genera that drive the global nitrogen cycle and hence soil fertility (de Vries and Bardgett 2012). Their activities are worth billions of dollars; why do they only rarely get a mention from conservationists? The biodiversity of nitrogen-processing bacteria contains species that may be engineered into crop plants, reducing the need for fertilizer (Beatty and Good 2011). Farmers worldwide rely (mostly unknowingly) on specific species of fungi to turn crop stubble into nutrients for the next season's crops (e.g., Pandey and Sinha 2008); *Aspergillus* and *Trichoderma* are two of the most important genera. Microbial ecologists are poised to greatly reduce farming costs by adding specific microbes to soils that suppress soil-borne crop pathogens (Mendes *et al.* 2011). Peak phosphorus has been proposed (Clabby 2010). As it is such a vital soil nutrient and if supplies are so limited, it would seem urgent to understand the microbes that drive the phosphorus cycle, especially in Australia (Smith *et al.* 2011; Khan *et al.* 2009). Fungal biodiversity alone appears to drive much ecosystem plant diversity, variability, and productivity (van der Heijden *et al.* 1998). Understanding how to conserve fungi was recognised as an urgent issue over 10 years ago (Hawksworth 1996). A study of the consequences of rainforest clearing for agriculture resonates with the Curtis quotation at the start of this article, as it emphasises that we do not know what to conserve, either for conservation or production, until the microbial biodiversity is known (Rodrigues *et al.* 2012).

Similar concepts and perhaps an even greater urgency apply to marine ecosystems where, for example, the cyanobacterium *Prochlorococcus* is one of the most abundant photosynthetic organism on Earth (Avrani *et al.* 2011). Taylor and Stocker (2012) lead their article on this issue with the statement: "*Bacteria play an indispensable role in marine biogeochemistry....*". The importance of research into this biodiversity is emphasised by recent results from environmental genomics which reveal previously unknown bacterial *phyla* (Wrighton *et al.* 2012).

Industrial Biodiversity

> *"Nature is the world's foremost designer. With billions of years of experience and boasting the most extensive laboratory available, it conducts research in every branch of engineering and science" (J. Bar-Cohen (2007) Biomimetics, Lavoisier, France).*

Energy: Biofuels have been highly contentious as crops previously grown for food have been diverted for highly profitable biofuel production. In contrast, research into microbial biodiversity has revealed organisms that use solar energy and a wide array of substrates, often waste materials, for biofuel production. The many promising alternatives include examples from bacterial, fungal, and algal biodiversity (Demain, 2000; Grayson *et al.* 2011; Wijffels and Barbosa 2010; Berka *et al.* 2011). Georgianna and Mayfield (2012) emphasise the vast genetic and metabolic diversity available in algal biodiversity alone.

Materials: Current exciting research has generated a wide array of medical and engineering materials derived from many microbes and invertebrates (e.g., www.oxfordbiomaterials.com). A major area of industrial research is biomineralization, the process whereby many kinds of invertebrates generate very hard material from their soft tissues, in ambient temperatures (e.g., Allen 2010). Especially interesting applications of this research are sponge spicules as models for optical fibres and mollusc nacre inspiring machine components (Aizenberg *et al.* 2004; Barthelat 2010). The field is wonderfully interesting and varied; for example, the transfer of moth eye technology to solar cells (Dewan, 2012).

Engineering: Invertebrate and microbial biodiversity is well regarded as a significant resource for thousands of projects in these fields, but only a few can be mentioned here. Knowledge of fire beetles has led to the development of a new generation of fire detectors, based on beetle technology, capable of detecting fires many kilometres distant (Klocke *et al.* 2011; Schmitz and Bousak 2012). Social insects have inspired design for engineers, computer scientists and architects (Holbrook *et al.* 2010). Arthropods are the focus of robotics research both for walking (e.g., Delcomyn 2004) and flying robots (e.g., www.fir.epfl.ch/home). Perhaps the most futuristic application of microbial technology is as arrays of bacterial colonies or 'biopixels' organised as low-cost biosensors (Prindle *et al.* 2012).

Mining and Bioremediation: Microbial biodiversity harbours many kinds of organisms that metabolise metal salts that can be utilised on an industrial scale to sequester metals from contaminated substrates. In the case of biomining, the substrates tend to be mine tailings in which inoculation with the appropriate bacteria such as *Leptospirillum* and *Ferroplasma* yield liquid 'cultures' from which precious or base metals are harvested (Rawlings and Johnson 2007; Reith *et al.*2009; http://bart.bangor.ac.uk/documents/Mining%20and%20 Microbiology)

Microbial biodiversity is also a crucial resource for the bioremediation industry and a wide variety of microbial species have been discovered that usefully metabolise a wide array of contaminants. Examples include *Deinococcus,* a bacterium widely used for the bioremediation of radioactive waste sites. (Brim *et al.* 2000); *Hymenoscyphus* and *Rhizopogon*, two soil fungi that break down depleted uranium in war-contaminated soils (Fomina *et al.* 2008); Cyanobacterial/Microalgal consortia developed for the control of many different industrial waste products (Subashchandrabose *et al.* 2011). *Pestalotiopsis* is the first fungus to survive only on polyurethane (plastic) waste (Russell *et al.* 2012).

Pharmaceuticals: This is perhaps the most familiar area of biodiversity exploration, although it is less known that most research effort has moved away from rainforest plants to the microbes and invertebrates of the oceans, seafloor, and extreme environments, all of which harbour immense metabolic and chemical diversity (e.g., Liu *et al.* 2010). The microbiome has emerged as a vital new area of research into microbial diversity as it affects the health of crop plants, endangered species – and ourselves. Each microbiome is the complex microbial community that inhabits the surfaces and interiors of all species. In most cases, the number of microbial cells of a microbiome greatly outnumber the cells of the organism with which it is associated. This new field explores microbial biodiversity both to understand the microbiome and to manage it, when necessary, with microbially-derived pharmaceuticals (Bascom-Slack *et al.* 2012; HMPC 2012; Waite *et al.* 2012).

Carbon Management: The sequestration of atmospheric carbon is an issue of global importance for the management of human-originated global warming. Bacteria, algae and fungi are important to the carbon cycle and hence major players in any strategy to regulate carbon, but the diversity of even the dominant groups is so poorly understood that we know nothing of any possible need for their conservation (e.g., Jiao *et al.* 2010).

Reasons for Including Microbial and Invertebrate Biodiversity in Conservation Science and Policy

1. **Conservation for Industry:** Currently, industries have little to no knowledge of the conservation status of most of the species upon which they depend.
2. **Explaining Ecosystem Services:** Inclusion tells us more about the organisms that actually provide ecosystem services, the mechanisms and groups involved (Vandermeer *et al.* 2010), that they are the major part of biodiversity and of such economic value that failing to understand and, if necessary, conserve them, threatens all human prosperity (Saunders and Walker 1998; Cardinale *et al.* 2012) .
3. **Core Economics.** Production industries - and many others - utilize microbial and invertebrate biodiversity in many ways. Biodiversity bioprospecting is no longer confined to the pharmaceutical industry and is carried out by a wide variety of industries seeking species, life-history traits, adaptations, metabolic pathways, enzymes, behaviours, structures, and materials, mainly among microbial and invertebrate biodiversity, in almost every ecosystem on Earth (Beattie and Ehrlich 2004). It is remarkable how few know of these worldwide activities, including my scientific colleagues.
4. **Resources.** Microbial and invertebrate biodiversity is a massive, largely unexplored resource for industry and for society. If in doubt, check out the journal *Biomimicry and Bioinspiration*, which is replete with engineering and medical projects largely based on these resources.
5. **Widening Responsibility for Conservation.** As biodiversity is a resource for many industries, its conservation is not just an issue for conventional conservation. Inclusion places it in sectors either not normally associated with it, or downright hostile to it. Biodiversity conservation becomes the concern for a far wider array of both public and private sectors.
6. **Good P.R. - the 'Attenborough Effect'**. Knowing the names and functions of some of the organisms provides a 'face' for ecosystem services. This might be called the 'Attenborough Effect' as it brings an organism into the spotlight and, even though small or ugly, enhances understanding and recognition of its importance. While the term 'ecosystem services' is of great value,

it does not necessarily strike the right note: One NSW farmer, when asked what it meant, answered: "Sounds like government interference to me". Further engagement with the public is gained through interest in the workings of ecological machines with so many different parts.

7. **Enemy Avoidance.** As long as biodiversity is presented to the world as a relatively small number of species, of concern mostly to relatively affluent groups that are easily and pejoratively labelled 'greenies', we continue to make unnecessary enemies of the individuals, lobby groups and industries who, because of that presentation, continue to be blind to its multiple economic benefits

Afterword

Biodiversity is the concept that integrates conservation and industry.

The economic and social benefits of microbial and invertebrate biodiversity are so great and pervasive that their inclusion in economic policy will help reduce the seemingly insurmountable costs of conventional biodiversity conservation (McCarthy *et al.* 2012). Its importance to such a wide range of industries places it at the core of global natural capital and its inclusion may be one of the transformative changes required to achieve the sustainability of global civilization (Ehrlich, Kareiva and Daily 2012).

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