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Why biodiversity has so many enemies

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Abstract

An estimated ninety percent of all species are either invertebrate or microbial but most conservation science and policy ignores them. This is disastrous for humanity as this biodiversity contains the majority of the genetic, chemical, metabolic and population diversity on Earth that is of enormous – and irreplaceable – economic importance. Microbes and invertebrates are at the core of all the primary industries and are the resource for a wide range of secondary industries. The low profile of these organisms has been attributed to the absence of technologies to handle them. This no longer applies. By including these organisms in mainstream conservation science and policy, several profound benefits accrue: 1) Informing the many biodiversity-based industries about the very species upon which they depend. 2) Showing these industries the extent of their actual and potential resource base. 3) Inform both industry and society on the 'nuts and bolts' of ecosystem services, the species involved, and their functions. 4) As industries recognise their reliance on biodiversity, the responsibility for biodiversity conservation is spread to sectors not normally associated with it. 5) It follows that it is in the self-interest of the biodiversity-based industries to protect their resources and to identify biodiversity conservation as core business. 6) Once this is achieved the conservation issues or crises among invertebrates and microbes, especially those crucial to ecosystem services or industry, can be identified. As long as biodiversity is erroneously presented as consisting of a few vertebrate and higher plant groups of concern chiefly to "conservationists", we continue to make unnecessary enemies of the individuals, lobby groups, political parties and industries who, because of that presentation, continue to be blind to its multiple and pervasive economic benefits.

Introduction

"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*).

A major omission in the Rio Convention of Biological Diversity (1992) was a clear statement that most species are either invertebrate or microbial. Perhaps even more important was the absence of any acknowledgement that these organisms 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). The numbers of species are so vast that even

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today nobody knows 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). Thus, conservation science largely ignores this majority, which is bad science, and any policy based on it must be bad policy.

Biodiversity conservation, be it in science, government departments or non-government organisations, the central operational proposition is that biodiversity is *de facto* subsets of flowering plant and vertebrate groups. In Australia, for example, biodiversity science and policy is mostly directed at vertebrate and higher plant groups, endangered species, remnant native vegetation, and the management of invasive species. Further, this biodiversity is often viewed as disease and pest organisms and therefore hardly a target for conservation (New 2006). How mistaken is this and why does it matter? It produces the absurd and tragic situation whereby a farmer, asked if his property harboured any biodiversity, answered along the lines, "Well, there are some patches of native vegetation which attract some birds and butterflies; a few nice species". The absurdity of this is that beneath his feet are thousands of microbial and invertebrate soil species. The tragedy is that these components of biodiversity, whose metabolic activities together regulate many aspects of the fertility, hydrodynamics and structure of his soil, remain unacknowledged even though they play a huge part in the productivity, yields and profits of his business. Worse still, farmers tend to encounter biodiversity conservation as legislation requiring particular remedial actions that are costly in terms of time and labour. A frequent perception is that biodiversity conservation is intrusion by outsiders – government departments, environmental organisations and academics. The fatal consequence of this bad science and policy is that few in the agricultural industries recognise that this biodiversity populates the human food chain or that their income is biodiversity-based.

This situation is largely because biodiversity is presented as subsets of the 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. 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*, now threatens a wide variety of native Australian plant species (Carnegie and Cooper 2011). When it comes to endangerment, 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. 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). It 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 very biodiversity of the soils upon which it depends.

This paper explores the worrying 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); rather than being an issue for many industries central to the economy and human well-being worldwide – a situation that recent history shows creates many unnecessary enemies.

A young science

Space travellers approaching Earth and interrogating their databanks for the number of species inhabiting the planet would arrive at a surprising answer: relatively little is known about this. Recent estimates of the numbers of species on Earth vary from 7 to 10 million and it is thought that 86% of terrestrial species and 91% of marine species still await discovery. Almost all estimates ignore the Archaea and the Bacteria and estimates of the number of fungal species are wobbly at around 1.5 million (Keeling et al. 2005; Mora et al. 2011). There appear to be about 6.1 million arthropod species (Basset et al. 2012) alone and each of these will harbour a complex microbial community or microbiome. The marine bacterium *Pelagibacter ubique* (Yooseph et al. 2010) appears to be the most common species on Earth and is essential to some global nutrient cycles but, because it is microscopic and planktonic, it is unknown to the public and indeed most scientists. The Archaea and the Bacteria are a serious challenge to biodiversity science as they exchange genes so freely that the category of 'species' may be difficult to apply (Lienau et al. 2011). As microbial diversity is understood its biodiversity, however measured, is likely to dwarf all other groups of organisms (Achtman et al. 2008).

Neglect of the invertebrates and microorganisms has been attributed to a lack of appropriate technologies but this no longer applies. Many kinds of invertebrates are now included in surveys through the application a wide range 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 situation for microorganisms is similar and the existing and new molecular systems for processing microscopic invertebrates and the Bacteria, Archaea, and Fungi are very exciting (e.g. Hayden 2012a,b; Boyer et al. 2012; Lozupone et al. 2012; Gewin 2012). Available high-speed methods already enable some aspects of microbial and invertebrate assessment and documentation. It is possible to 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 with a view to determining serious changes in frequency if not their actual level of vulnerability to extinction, locally or otherwise (e.g. Tilman et al. 1999; Fierer et al. 2013).

Biodiversity and Primary Industry

The host of mostly tiny species that provide ecosystem services such as the regulation of soil fertility, structure and moisture content that are the foundation of all primary production industries could be called 'production biodiversity' or 'agro-biodiversity' (Thaman 2014). Many different groups of microbes and invertebrates are involved but, because these components of biodiversity are so rarely studied by conservation science, we do not know their conservation status. It is becoming clear that some agricultural methods affect the diversity of soils microbes, for example, the application of industrially produced nitrogenous fertilizers can reduce the activities of beneficial microbes (e.g. Carreiro et al. 2000; Fierer et al. 2013).

The economic values of arthropods, especially insects, have been assessed with respect to their services as pollinators, biological control agents, the burial of the dung of exotic species such as cows and sheep, and their participation in the food chains of vertebrate species around which there are major recreational hunting and fishing industries (e.g. Isaacs et al. 2009; Losey and Vaughan 2006). These services are known to be worth many billions of dollars annually in the USA, and include groups not normally regarded as economic assets, such as beetles and flies.

The critical importance of wild pollinators to crops around the world is now better appreciated. The decline of the honeybee in many nations means that farmers and orchardists are searching for alternatives, especially among native bees, generally from genera other than the honeybee. However, many kinds of insects are good pollinators, if only because they fly from flower to flower in very large numbers. They include 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).

An important issue often missed by conservationists is the two-way interactions between crops and wild pollinators. With respect to benefits flowing from wild pollinators to crops, significant increases in yields 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). In addition, global dependence on wild pollinators is increasing (Aizen et al. 2008). Although few crops rely exclusively on wild pollinators, yield increases in nearly all of these crops resulting from the activities of wild pollinators are important economically (Klein et al 2007) Thus it is beneficial to retain native vegetation in croplands for the provision of native pollinator habitat (Garibaldi et al. 2010, 2011).

With respect to the benefits of crops to wild species, the situation is 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). While the benefits have been assessed mainly for insects, it seems that other kinds of nectar and pollen feeding animals might also accrue. Further, agricultural land has multiple benefits for wild bees and wasps (Steffan-Dewenter 2003; Mandelik et al. 2012). This area of research needs more attention.

Most biological control agents, especially those deployed among crops, are either microbial or invertebrate. This means that the major alternative to chemical pesticides resides within this vast biodiversity (Bellows and Fisher, 1999). A wide array of these organisms have been deployed for centuries (eg Beattie 1985), are already cultured in vast numbers for application to crops and orchards (e.g. http: //www.bugsforbugs.com.au) or are in the trial phase either as sole agents or for inclusion in integrated pest management schemes as shown regularly in the journal: http: //www.journals.elsevier.com/biological-control/. Bellows and Fisher (1999), a standard text on biological control agents, shows that arthropod biodiversity is a vast resource for pest control and it is rarely appreciated that mites and wasps, two groups generally regarded with hostility, are vast commercial resources containing very large numbers of parasitic species, most of which are highly specialised on their hosts, thus reducing the possibilities of disastrous 'escapes' such as the cane toad fiasco. Beetles are utilised on an industrial scale for dung control throughout the world (Nichols et al. 2008). The venoms of spiders have emerged as potential insecticides, being hyper-stable mini-proteins that target novel sites in specific pest insects. As there are roughly 100,000 spider species worldwide, there is a very large available resource base (Windley et al. 2012).

Ants can be biological control agents, but managing them can be difficult (e.g. Majer, 1986; Rico-Gray and Oliveira 2007). Together with termites, they 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 diverse range 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. The importance of earthworms to soil fertility has been known for centuries but it is only more recently that the beneficial activities of nematode worms, mites, springtails, beetles, termites, millipedes, centipedes, spiders and ants, cumulatively hundreds of thousands of species, have been documented. 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 et al. 2004). Many marine substrates are inhabited by entire phyla that are little known even to biologists; what they contribute is anyone's guess.

Microbial contributions to primary production industries are less well studied, but the pivotal 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). As their activities are worth billions of dollars and their conservation status is unknown, they surely should be on the conservation agenda. While it may be that these genera are not endangered, local extinctions resulting from human activity are likely. 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). Phosphorus is such a vital soil nutrient, especially in Australia, it is important to understand the microbes that drive the phosphorus cycle, especially as 'Peak Phosphorus' has been proposed (Clabby 2010; Smith et al 2011; Khan et al. 2009). Fungal biodiversity drives much ecosystem plant diversity, variability, and productivity (van der Heijden et al 1998) and is the resource for a major pest control industry (e.g. Remadevi et al. 2010).

The need to understand how to conserve fungi has been recognised for some time (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 organisms on Earth (Avrani et al. 2011). 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; Taylor and Stocker 2012).

Biodiversity and Secondary Industries

"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)

Biodiversity and Energy: Research into microbial biodiversity has revealed a wide range of organisms that use solar energy and many different kinds of substrates, including 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.

Biodiversity and Materials: This is a very exciting research field that is generating a wide array of medical and engineering materials derived from various microbes and invertebrates (e.g. http: //www.oxfordbiomaterials.com). Biomineralization, for example, is the process whereby soft-bodied invertebrates generate very hard materials such as shells and mouthparts, and is the focus of many research laboratories puzzled as to how the animals achieve this at ambient temperatures and without the large-scale application of high pressures and environmentally harmful chemicals that current manufacturing demands (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).

Biodiversity and Engineering: As with energy and materials, industry appears to be far more aware of the potential of invertebrate and microbial biodiversity for its needs than biologists and recognise it as a significant resource for thousands of projects, only a few can be mentioned here. Knowledge of fire beetles has lead 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. http: //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).

Biodiversity, 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. In biomining the substrates are often mine tailings where inoculation with 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%20Microbiology

The bioremediation industry also exploits microbial biodiversity and a wide variety of microbial species have been discovered that usefully metabolise many kinds of toxic 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).

Biodiversity and the Pharmaceutical Industry: This is classical bioprospecting and the most familiar area of biodiversity exploration, although most research 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 is the complex community of microbes that inhabits the surfaces and interiors of all species, including crop plants, endangered species – and ourselves, and is an exciting new area of research into microbial biodiversity. Very often, the numbers of microbial cells of a microbiome greatly outnumber the cells of the organism with which it is associated. Current research is exploring microbial biodiversity 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).

Biodiversity and Carbon Management: Bacteria, algae and fungi are all major players in the global carbon cycle. In this context too they are essential to the survival of humanity, but the diversity of even the dominant groups is still poorly understood and almost nothing is known of any possible need for their conservation (e.g. Jiao et al. 2010).

The importance of including microbial and invertebrate biodiversity in conservation can perhaps be summarised under six headings:

1. Inform

To inform the biodiversity-based industries with the knowledge of the species upon which they depend. Primary and many other industries utilize microbial and invertebrate biodiversity as basic resources 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 every ecosystem on Earth (Beattie and Ehrlich 2004).

2. Explain

To explain ecosystem services in terms of the actual organisms that provide them and the mechanisms and functions involved (Vandermeer et al. 2010). In this context, the practical economic values of this major sector of biodiversity becomes manifest (Saunders and Walker 1998; Cardinale et al. 2012).

3. Reveal

To reveal the vast resources to be found in microbial and invertebrate biodiversity. If in doubt, check out the journal *Bioinspiration and Biomimetics* (http://iopscience.iop.org/1748-3190/) which is replete with engineering and medical projects largely based on these resources.

4. Increase conservation

To spread the responsibility for conservation**.** As biodiversity is a resource for many industries, its conservation is not just an issue for conventional conservation organisations. Inclusion places it in sectors either not normally associated with it. Biodiversity conservation becomes the concern for a far wider array of both public and private sectors.

5. Reduce enemies

As long as biodiversity is presented to the world as a 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 - and even to the fact that they depend on it.

6. Action

Finally reveal the conservation status of microbial and invertebrate species, especially those critical to society and industry. While it seems unlikely that many of these species are endangered globally, some appear to be going extinct locally or even regionally. Local extinction of critical species, such as nitrogen-fixers, is often costly and, as has been shown with earthworms, leads to widespread replacement by exotic species.

Biodiversity is a 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 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 could be one of the transformative changes required to achieve the sustainability of global civilization (Ehrlich, Kareiva and Daily 2012).

References

Achtman M, Wagner M. (2008) Microbial diversity and the genetic nature of microbial species. *Nature Reviews Microbiology* 6: 431–440.

Aizen MA, Garibaldi LA, Cunningham SA et al. (2008) Long-term global trends in crop yield and production reveal no current pollination shortage but increasing pollination dependency, *Current Biology* 18: 1572–1575. http: //dx.doi.org/10.1016/j.cub.2008.08.066

Aizenberg J, Sundar VC, Yablon A. et al. (2004) Biological glass fibres. *PNAS* 101: 3358–3363. http: //dx.doi.org/10.1073/pnas.0307843101

Allen R. (ed) (2010) *Bulletproof Feathers: How Science Uses Nature's Secrets to Design Cutting-Edge Technology*. University of Chicago Press, Chicago.

Avrani S, Wurtzel O, Sharon I. et al. (2011) Genomic island variability facilitates *Prochlorococcus* – virus coexistence. *Nature* 474: 604–608. http: //dx.doi.org/10.1038/nature10172

Barthelat F (2010) Nacre from mollusc shells: a model for high-performance structural materials. *Bioinspiration and Biomimicry* doi: 10.1088/1748-3182/5/3035001

Bascom-Slack CA, Arnold AE, Strobel SA (2012) Student-directed discovery of the plant microbiome and its products. *Science* 338: 485–486. http: //dx.doi.org/10.1126/science.1215227

Beattie AJ (1985) *The Evolutionary Ecology of Ant-Plant Mutualisms.* (Cambridge University Press). http: //dx.doi.org/10.1017/CBO9780511721878

Beattie AJ, Ehrlich PR (2004) *Wild Solutions: Why Biodiversity is Money in the Bank.* (Yale University Press, Newhaven, USA; Melbourne University Press, Melbourne, Australia).

Beatty PH, Good AG (2011) Future prospects for cereals that fix nitrogen. *Science* 333: 416–417. http: //dx.doi.org/10.1126/science.1209467

Berka RM, Grigoriev IV, Otilla, R. et al. (2011) Comparative genomic analysis of the thermophilic biomass-degrading fungi *Myceliophthora thermophila* and *Thielavia terrestris*. *Nature Biotechnology* 29: 922–927. http: //dx.doi.org/10.1038/nbt.1976

Biello D (2012) Putting the sting on mealy marauders: Thailand unleashes South American wasps to save its Cassava crop. *Scientific American* 21 July.

Blanche R, Cunningham SA (2005) Rain forest provides pollinating beetles for Atemoya crops. *Journal of Economic Entomology* 98: 1193–1201. http: //dx.doi.org/10.1603/0022-0493-98.4.1193

Blanche R, Ludwig JA, Cunningham SA (2006) Proximity to rainforest enhances pollination and fruit set in orchards. *Journal of Applied Ecology* 43: 1182–1187. http: //dx.doi.org/10.1111/j.1365-2664.2006.01230.x

Boyer S Brown SD, Collins RA et al. (2012) Sliding window analyses for optimal selections of mini-barcodes, and application to 454-pyrosequencing for specimen identification from degraded DNA. *PLoS ONE* 7(5) e38215. http: //dx.doi.org/10.1371/journal.pone.0038215

Brim H, McFarlan S, Fredrickson JK et al. (2000) Engineering *Deinococcus radiodurans* for metal remediation in radioactive mixed waste environments. *Nature Biotechnology* 18: 85–90. http: //dx.doi.org/10.1038/71986

Cardinale BJ, Duffy JE, Gonzalez A. et al. (2012) Biodiversity loss and its impact on humanity. *Nature* 486: 59–67. http: //dx.doi.org/10.1038/nature11148

Carnegie AJ, Cooper K (2011) Emergency response to the incursion of an exotic myrtaceous rust in Australia. *Australasian Plant Pathology* 40: 346–359. http: //dx.doi.org/10.1007/s13313-011-0066-6

Carreiro MM, Sinsabaugh RL, Repert DA et al. (2000) Microbial enzyme shifts explain litter decay responses to simulated nitrogen deposition. *Ecology* 81: 2359–2365. http: //dx.doi.org/10.1890/0012-9658(2000)081[2359: MESELD]2.0.CO;2

Clabby C (2010) Does peak phosphorus loom? *American Scientist* 98: 291.

Collen B, Bohra M, Baillie JEM (eds.) (2012) Spineless: Status and Trends of the World's Invertebrates. Zoological Society of London. U.K.

Colwell R (1997) Biota 4d: Biota Software Program. Sinauer Associates Inc., New York.

Costello MJ, May RM, Stork NE (2013) Can we name Earth's species before they go extinct? *Science* 339: 413–416. http: //dx.doi.org/10.1126/science.1230318

De Deyn GB, Raaijmakers CE, Zoomer HR, Berg MP, de Ruiter PC, Verhoef HA, Bezemer TM, van der Putten WH (2003) Soil invertebrate fauna enhances grassland succession and diversity. *Nature* 422: 711–713. http: //dx.doi.org/10.1038/nature01548

Delcomyn F (2004) Insect walking and robotics. *Annual Review of Entomology* 49: 51–70. http: //dx.doi.org/10.1146/annurev.ento.49.061802.123257

Demain AL (2000) Small bugs, big business: the economic power of the microbe. *Biotechnology Advances* 18: 499–514. http: //dx.doi.org/10.1016/S0734-9750(00)00049-5

De Vries FT, Bardgett RD (2012) Plant-microbial linkages and ecosystem nitrogen retention. *Frontiers in Ecology and Environment* 10: 425–432. http: //dx.doi.org/10.1890/110162

Dewan R, Fische S, Meyer-Rochow VB, **Özdemir Y, Hamraz S, Knipp D** (2012) Studying nanostructured nipple arrays of moth eye facets helps to design better then film solar cells. *Bioinspiration and Biomimicry* 7: 016003. http://dx.doi.org/%2010.1088/1748-3182/7/1/016003

Ehrlich PR, Kareiva PM, Daily GC (2012) Securing natural capital and expanding equity to rescale civilization. *Nature* 486: 68–73. http: //dx.doi.org/10.1038/nature11157

Evans TA, Dawes TZ, Ward PR, Lo N (2011) Ants and termites increase crop yield in a dry climate. *Nature Communication.* 2: 262. http: //dx.doi.org/10.1038/ncomms1257

Fierer N, Ladau J, Clements JC et al. (2013) Reconstructing the microbial diversity and function of pre-agricultural Tallgrass Prairie soils in the United States. *Science* 342: 621–624. http: //dx.doi.org/10.1126/science.1243768

Fomina M, Charnock JM, Hillier S (2008) Role of fungi in the biogeochemical fate of depleted uranium. *Current Biology* 18: R375–R377. http: //dx.doi.org/10.1016/j.cub.2008.03.011

Freeman MF, Gurgui C, Maximilian JH et al. (2012) Metagenome mining reveals polytheonamides as post-translationally modified ribosomal peptides. *Science* 338: 387–390. http: //dx.doi.org/10.1126/science.1226121

Garibaldi LA, Steffan-Dewenter I, Kremen C. et al. (2011) Stability of pollination services decreases with isolation from natural areas despite honeybee visits. *Ecology Letters* 14: 1062–1072. http: //dx.doi.org/10.1111/j.1461-0248.2011.01669.x

Garibaldi LA, Aizen MA, Klein AM et al. (2010) Global growth and stability of agricultural yield decrease with pollinator dependence. *PNAS* 108: 5909–5914. http: //dx.doi.org/10.1073/pnas.1012431108

Georgianna DR, Mayfield SP (2012) Exploiting diversity and synthetic biology for the production of algal biofuels. *Nature* 488: 329–335. http: //dx.doi.org/10.1038/nature11479

Gewin V (2012) The sequencing machine. *Nature* 487: 156–158. http: //dx.doi.org/10.1038/487156a

Grayson M (2011) Biofuels: Sowing substitutes for fossil fuels. *Nature Outlook* 474: S1–S25. http: //dx.doi.org/10.1038/474S01a

Hawksworth DL (1996) Microorganisms: the neglected rivets in ecosystem maintenance. In: *Biodiversity, Science and Development,* di Castri, F. and Younes, T. (eds.) (CAB International, UK).

Hayden EC (2012a) Nanopore genome sequencer makes its debut. *Nature Biotechnology* 18: 630–634.

Hayden EC (2012b) Next-generation genome sequences compared. *Nature* 507: 294–295.

Heard TA, Vithanage V, Chacko EK (1990) Pollination biology of Cashew in the Northern Territory of Australia. *Australian Journal of Agricultural Research* 41: 1101–1114. http: //dx.doi.org/10.1071/AR9901101

HMPC (2012) – The Human Microbiome Project Consortium. Structure, function and diversity of the healthy human microbiome. *Nature* 486: 207–214. http: //dx.doi.org/10.1038/nature11234

Holbrook CT, Clark RM, Moore D et al. (2010) Social insects inspire human design. *Biology Letters*: 431–433. http: //dx.doi.org/10.1098/rsbl.2010.0270

Isaacs R, Tuell J, Fiedler A et al. (2009) Maximizing arthropod-mediated ecosystem services in agricultural landscapes: the role of native plants. *Frontiers in Ecology and the Environment* 7: 196–203. http: //dx.doi.org/10.1890/080035

Jeschke JM, Aparicio LG, Haider S et al. (2012) Taxonomic bias and lack of cross-taxonomic studies in invasion biology. *Frontiers in Ecology and the Environment* 10: 349–350. http: //dx.doi.org/10.1890/12.WB.016

Jiao N, Herndl GJ, Hansell DA. et al. (2010) Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean. *Nature Reviews Microbiology* 8: 593–599. http: //dx.doi.org/10.1038/nrmicro2386

Kean JM, Vink CJ, Till C (2012) Real-time remote diagnostics for ecology. *Frontiers in Ecology and the Environment* 10: 99–104. http: //dx.doi.org/10.1890/110065

Keeling PJ, Burger G, Durnford DG et al. (2005) The tree of eukaryotes. *Trends in Ecology and Evolution* 12: 670–676. http: //dx.doi.org/10.1016/j.tree.2005.09.005

Kennedy C, Lonsdorf E, Neel M. et al. (2013) A global quantitative synthesis of local and landscape effects on native bee pollinators in agroecosystems. *Ecology Letters* (in press). http: //dx.doi.org/10.1111/ele.12082

Khan AA, Jilani G, Akhtar MS et al. (2009) Phosphorus solubilising bacteria: occurrence, mechanisms and their role in crop production. *Journal of Agricultural and Biological Science* 1: 48–58.

Klein AM, Vaissiere BE, Cane JH et al. (2007) Importance of pollinators in changing landscapes for world crops. *Proceedings Royal Society B* 274: 303–313. http: //dx.doi.org/10.1098/rspb.2006.3721

Klocke D, Schmitz A, Soltner H. et al. (2011) Infrared receptors in pyrophilous (fire-loving) insects as a model for new un-cooled infrared sensors. *Beilstein Journal of Nanotechnology* 2: 186–197. http: //dx.doi.org/10.3762/bjnano.2.22

Lavelle P, Dangerfield M, Fragoso C et al. (1994) The relationship between soil macrofauna and tropical soil fertility. In: *The Biological Management of Tropical Soil Fertility,* Woomer, P.L. and Swift, M.J. (eds.) pp 137–169. (Wiley-Sayce, New York).

Lawton JH, Bignell DE, Bloemers GF et al. (1996) Carbob flux and diversity of nematodes and termites in Cameroon forest soils. *Biodiversity and Conservation* 5: 261–273. http: //dx.doi.org/10.1007/BF00055835

Lienau EK, et al. (2011) The mega-matrix of life: using genome-scale horizontal gene transfer and sequence evolution data as information about the vertical history of life. *Cladistics* 27: 417–427. http: //dx.doi.org/10.1111/j.1096-0031.2010.00337.x

Liu X, Ashforth E, Ren B et al. (2010) Bioprospecting microbial natural products libraries from the marine environment for drug discovery. *Journal of Antibiotics* 63: 415–422. http: //dx.doi.org/10.1038/ja.2010.56

Lohrer AM, Thrush SF, Gibbs MM (2004) Bioturbators enhance ecosystem function through complex biogeochemical interactions. *Nature* 431: 1092–1096. http: //dx.doi.org/10.1038/nature03042

Losey JE, Vaughan M (2006) The economic value of ecological services provided by insects. *BioScience* 56: 311–323. http: //dx.doi.org/10.1641/0006-3568(2006)56[311: TEVOES]2.0.CO;2

Lozupone CA, Stombough SJ, Jansson JK et al. (2012) Diversity, stability and resilience of the human gut microbiota. *Nature* 489: 220–230. http: //dx.doi.org/10.1038/nature11550

Majer JD (1986) Utilising economically beneficial ants. In: S. Bradleigh-Vinson (Ed.) *Economic Impact and Control of Social Insects*. Pp. 314–331. (Praeger, New York).

Mandelik Y, Winfree R, Neeson,T, Kremen, C. (2012) Complementary habitat use by wild bees in agro-natural landscapes. *Ecological Applications* 22: 1535–1546. http: //dx.doi.org/10.1890/11-1299.1

McCarthy DP, Donald PF, Scharlemann JPW et al. (2012) Financial costs of meeting global biodiversity conservation targets. *Science* 338: 946–949. http: //dx.doi.org/10.1126/science.1229803

Mendes R, Kruijt M, de Bruijn I et al. (2011) Deciphering the rhizosphere microbiome for disease-suppressive bacteria. *Science* 332: 1097–1100. http: //dx.doi.org/10.1126/science.1203980

Mora C, Tittensor DP, Adl S, Simpson AGB, Worm B (2011) How many species are there on Earth and in the ocean? PLoS Biol. 9(8) e1001127. http: //dx.doi.org/10.1371/journal.pbio.1001127

New TR (2006) Conservation Biology in Australia. Oxford University Press.

Nichols E, Spector S, Louzada J et al. (2008) Ecological functions and ecosystem services provided by Scarabaeinae dung *beetles. Biological Conservation* 141: 1461–1474. http: //dx.doi.org/10.1016/j.biocon.2008.04.011

Oliver I, Beattie AJ (1996) Designing a cost-effective invertebrate survey: a test of methods for the rapid assessment of biodiversity. *Ecological Applications* 6: 594–607. http: //dx.doi.org/10.2307/2269394

Oliver I, Pik A, Britton D. et al. (2000) Virtual biodiversity assessment systems. *Bioscience* 50: 441–450. http: //dx.doi.org/10.1641/0006-3568(2000)050[0441: VBAS]2.0.CO;2

Pandey V, Sinha A (2008) Mycoflora associated with decomposition of rice stubble mixed with soil. *Journal of Plant Protection Research* 48: 247–253. http: //dx.doi.org/10.2478/v10045-008-0028-3

Ponder W, Lunney D (1999) The Other 99%. Published by the Royal Zoological Society of New South Wales. (Surrey Beatty and Sons, Chipping Norton, Australia).

Prindle A, Samayoa P, Razinkov I et al. (2012) A sensing array of radically coupled genetic 'biopixels'. *Nature* 481: 39–44. http: //dx.doi.org/10.1038/nature10722

Pyšek P, Richardson DM, Pergl J et al. (2008) Geographical and taxonomic biases in invasion ecology. *TREE* 23: 237–244. http: //dx.doi.org/10.1016/j.tree.2008.02.002

Ramankutty N, Rhemtulla J (2012) Can intensive farming save nature? *Frontiers in Ecology and the Environment* 10: 455. http: //dx.doi.org/10.1890/1540-9295-10.9.455

Rawlings DE, Johnson DB (2007) The microbiology of biomining. *Microbiology* 153: 315–324. http: //dx.doi.org/10.1099/mic.0.2006/001206-0

Redford KH, Jensen DB, Breheny JJ (2012) Integrating the captive and the wild. *Science* 338: 1157–1158. http: //dx.doi.org/10.1126/science.1228899

Reith F, Etschmann B, Grosse C et al. (2009) Mechanisms of gold biomineralization in the bacterium *Cupriavidus metallidurans*. *PNAS* http: //dx.doi.org/10.1073/pnas.0904583106

Remadevi OK, Sasisharan TO, Balachander M (2010) *Metarhizium*-based mycoinsecticides for forest pest management. *Journal of Biopesticides* 3: 470–473.

Ricketts TH,Regetz J, Steffan-Dewenter I et al. (2008) Landscape effects on crop pollination services: are there general patterns? *Ecology Letters* 11: 499–515. http: //dx.doi.org/10.1111/j.1461-0248.2008.01157.x

Rico-Gray V, Oliveira PS (2007) *The Ecology and Evolution of Ant-Plant Interactions*. (University of Chicago Press, Chicago). http: //dx.doi.org/10.7208/chicago/9780226713540.001.0001

Rodrigues JLM, Pellizari VH, Mueller R et al. (2012) Conversion of the Amazon rainforest to agriculture results in biotic homogenization of soil bacterial communities. *PNAS* 110: 988–993. http: //dx.doi.org/10.1073/pnas.1220608110

Russell JR, Huang J, Anand P et al. (2011) Biodegradation of polyester polyurethane by endophytic fungi. *Applied **and** Environmental Microbiology* 77: 6076–6084. http: //dx.doi.org/10.1128/AEM.00521-11

Saunders D, Walker B (1998) Biodiversity and Agriculture. *Reform* 6: 11–16. National Farmers Federation.

Schmitz H, Bousak H (2012) Modelling a historic oil-tank fire allows estimation of the sensitivity of the infrared receptors in pyrophilous *Melanophila* beetles. *PLoS ONE* 7(5) e37627. Doi: 10.1371/journal.pone.0037627.

Smith S, Jakobsen I, Gronlund M et al. (2011) Roles of arbuscular mycorrhizas in plant phosphorus nutrition. *Plant Physiology* 156: 1050–1057. http: //dx.doi.org/10.1104/pp.111.174581

Steffan-Dewenter I (2003) Importance of habitat area and landscape context for species richness of bees and wasps in fragmented orchard meadows. *Conservation Biology* 17: 1036–1044. http: //dx.doi.org/10.1046/j.1523-1739.2003.01575.x

Stinner BJ, House GJ (1990) Arthropods and other invertebrates in conservation-tillage agriculture. *Annual Review of Entomology* 35: 299–318). http: //dx.doi.org/10.1146/annurev.en.35.010190.001503

Subashchandrabose SR, Ramakrishnan B, Megharaj M et al. (2011) Consortia of cyanobacteria/microalgae and bacteria: biotechnological potential. *Biotechnology Advances* 29: 896–906. http: //dx.doi.org/10.1016/j.biotechadv.2011.07.009

Thaman R (2014) Agrodeforestation and the loss of agrobiodiversity in the Pacific Islands: a call for conservation. *Pacific Conservation Biology* 20: 180–192.

Taylor JR, Stocker R (2012) Trade-offs of chemotactic foraging in turbulent water. *Science* 338: 675–679. http: //dx.doi.org/10.1126/science.1219417

Van der Heijden MGA, Klironomos JN, Ursic M et al. (1998) Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity. *Nature* 396: 69–72. http: //dx.doi.org/10.1038/23932

Vandermeer J, Perfecto I, Philpott S (2010). Ecological complexity and pest control: uncovering an autonomous ecosystem service. *BioScience* 60: 527–537. http: //dx.doi.org/10.1525/bio.2010.60.7.8

Waite DW, Deines P, Taylor MW (2012) Gut microbiome of the critically endangered New Zealand parrot, the Kakapo. *PLoS ONE* doi: 10.1371/journal.pone.0035803. http: //dx.doi.org/10.1371/journal.pone.0035803

Westphal C, Steffan-Dewenter I, Tscharntke T (2003) Mass flowering crops enhance pollinator densities at a landscape scale. *Ecology Letters*: 961–965. http: //dx.doi.org/10.1046/j.1461-0248.2003.00523.x

Whitford WG (1996) The importance of the biodiversity of soil biota in arid ecosystems. *Biodiversity and Conservation* 5: 185–195. http: //dx.doi.org/10.1007/BF00055829

Wijffels RH, Barbosa MJ (2010) An outlook on microalgal biofuels. *Science* 329: 796–799. http: //dx.doi.org/10.1126/science.1189003

Windley MJ, Herzig V, Dziemborowicz SA et al. (2012) Spider venom peptides as bioinsecticides. *Toxins* 4: 191–227. http: //dx.doi.org/10.3390/toxins4030191

Wrighton KC, Thomas BC, Sharon I et al. (2012) Fermentation, hydrogen, and sulphur metabolism in multiple uncultivated bacterial phyla. *Science* 337: 1661–1665. http: //dx.doi.org/10.1126/science.1224041

Yooseph S, Nealson KH, Rusch DP et al. (2010) Genomic and functional adaptations in surface planktonic prokaryotes. *Nature* 468: 60–66. http: //dx.doi.org/10.1038/nature09530

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