Functional Ecology

British Ecological Society

*Functional Ecology* 2010, **24**, 947–949 doi: 10.1111/j.1365-2435.2010.01772.x

EDITORIAL

# The ecological significance of antioxidants and oxidative stress: a marriage between mechanistic and functional perspectives

**Kevin J. McGraw[1,*], Alan A. Cohen[2], David Costantini[3] and Peeter Hõrak[4]**

[1]*School of Life Sciences, Arizona State University, Tempe, AZ 85287-4501, USA;* [2]*Groupe de recherche PRIMUS, Centre Hospitalier Universitaire de Sherbrooke, 3001 12 e Ave Nord, Sherbrooke, Quebec J1H 5N4, Canada;* [3]*Division of Ecology and Evolutionary Biology, Faculty of Biomedical and Life Sciences, University of Glasgow, Graham Kerr Building, Glasgow G12 8QQ, UK; and* [4]*Institute of Ecology and Earth Sciences, Tartu University, Vanemuise 46, 51014 Tartu, Estonia*

Since the 1970s, ecological disciplines have expanded not only into more functional realms, but also to include many technical, mechanistic perspectives (Porter *et al.* 1973). Technological and conceptual advances – from ecological stoichiometry (Sterner & Elser 2002) to stable isotope measurement (Peterson & Fry 1987; Engel *et al.* 2009) – have paved the way for improved understandings of the molecular currencies with which organisms interact with their environment, with subdisciplines like nutritional ecology and physiological ecology especially benefitting. Several of these modern breakthroughs are vital not just for basic research, but for applied science as well, as the current Earth's climate warms, habitats are altered, and as organisms cope with these rapid changes to their thermal and nutritional surroundings.

Among the newest of these blossoming ecological areas are 'antioxidant ecology' and 'oxidative-stress ecology'. These sister fields combine to address the fundamental premise that free-ranging organisms are engaged in a molecular battle with free-radicals and other reactive chemical species that are produced by basic metabolic activities. Some such molecules provide key functions in the body (e.g. cell signalling), while others accumulate to damage macromolecules, cells, and tissues. Antioxidant sources – both exogenous (e.g. diet) and endogenous (e.g. enzymes, hormones) – work to offset deleterious effects by quenching reactive species. Biological studies of antioxidants (AOs) and oxidative-stress (OS) have a long history (see Costantini *et al.* 2010 in this issue for a review), but until recently occurred largely outside of natural contexts (e.g. for biomedical purposes, under *in-vitro* conditions, to improve longevity of domesticated/captive animals). This initial focus, spanning much of the 20th century, was quite practical, as sources and fluxes of AOs and OS are much more tractable under confined conditions.

Within the last few decades, however, we have seen the merger of these lab biochemical and physiological approaches to AOs and OS with ecological principles. Researchers have had to start from the beginning for virtually every taxon, challenged with answering basic questions about natural sources of variation in AOs and OS. How do these molecules vary as a function of species, sex, age, developmental stage, season, time of day, or habitat, for example? And while AOs and OS have clear links to survival and reproduction in the lab, does this hold for organisms in their natural environments? These questions are non-trivial to ask in free-ranging systems, due to the highly dynamic and compartmentalized nature of AO and OS systems. Even compared to other rapidly shifting systems in physiological ecology (e.g. thermal, hormonal, immunological), AO and OS systems are among the most challenging to assess comprehensively, with their sub-second rates of change, diverse types and body-region specificity.

Given such immense room for description and development in these fields, a wave of interest in AO and OS ecology has emerged. The primary literature paints a vivid picture of the youth and explosiveness of the fields of antioxidant ecology and oxidative-stress ecology. In a recent survey using the Web of Science, we found that all papers keyworded to contain the words 'antioxidant*' and 'ecolog*' or 'oxidative stress' and 'ecolog*' (amounting to 274 and 321 in all, respectively), have appeared in the literature since 1990 (Fig. 1). Moreover, more than 85% of papers from these fields were published in the 2000s (Fig. 1). A fair number of these listings, however, still were biomedically or biochemically focused. When we further examined this 20-year literature history by filtering out those articles not dealing with natural environmental issues, the lists were whittled down to 179 and 285 total publications respectively (Fig. 1). As further evidence of an ecological shift in the new millennium, only 38% (15/39) of the pre-2000 papers were published on antioxidant ecology *per se*, whereas 70% (164/235) of the post-1999 papers had an ecological emphasis (Fig. 1). The same was generally true for OS publications as well, though these articles were quite highly centred on ecology both before (78%, 14/18) and after 2000 (89%, 271/303).

These are impressive rates of acceleration for a newborn field that barely existed in the scientific literature just 10 years

*Correspondence author. E-mail: kevin.mcgraw@asu.edu

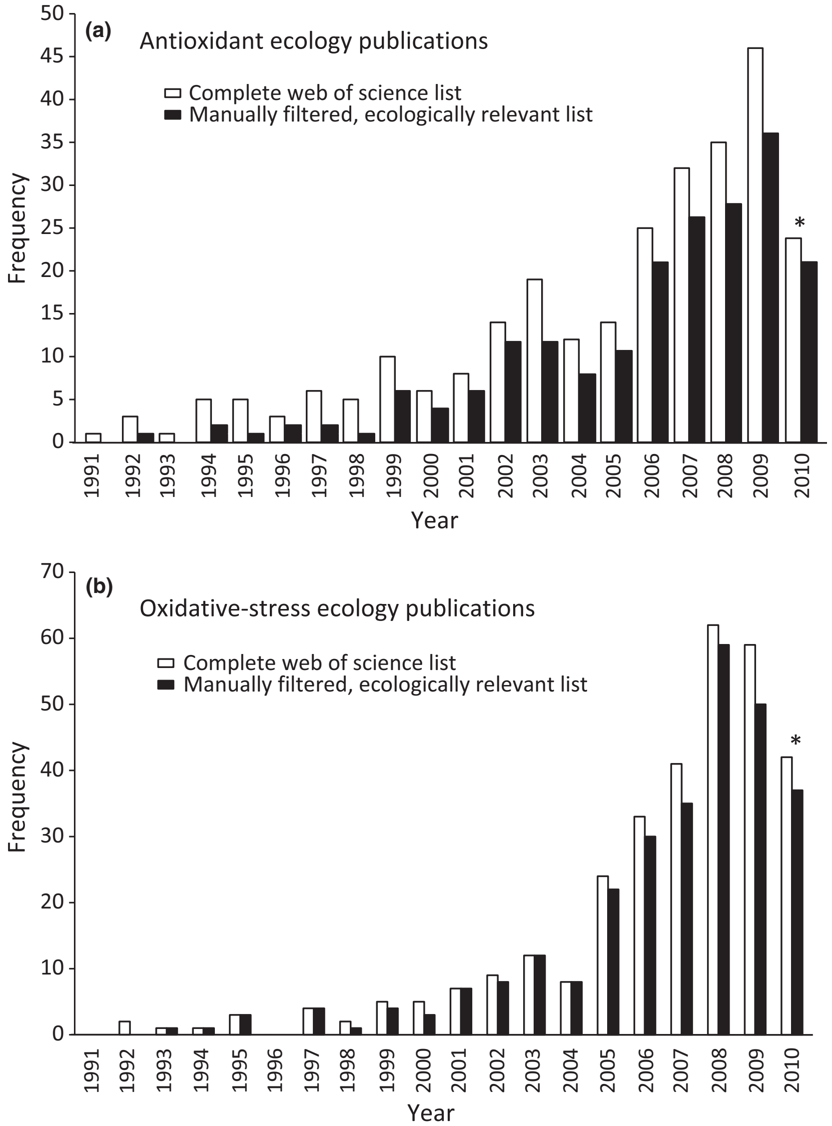


**Fig. 1.** Frequency distribution of published papers on (a) 'antioxidant ecology' and (b) 'oxidative-stress ecology', as revealed by a database search on 15 July 2010 using the Web of Science® search engine (ISI Web of Knowledge$^{SM}$; Thomson Reuters, Philadelphia, PA, USA), which contains primary science journal articles published since 1899. These distributions are not completely independent, as many papers address issues in both antioxidants and oxidative stress. Asterisks indicate that only a partial year of data was available for 2010.

ago. Even the terms for these fields – antioxidant ecology and oxidative-stress ecology – took quite a while to emerge; a Web of Science search for these precise word strings in mid-July 2010 turned up only 49 and 73 total publications respectively. There are now whole research groups at institutions, such as The Antioxidant Ecology group at the University of Glasgow in Scotland, dedicated to this emergent scientific endeavour.

May Berenbaum and colleagues can be credited with many of the first publications on AO ecology, aimed at understanding insect antioxidant systems and how these animals cope with host plant defenses (i.e. detoxifying secondary defensive compounds) (Lee & Berenbaum 1990, 1993). Publication rates remained consistently low until the turn of the century, when seminal papers like Olson & Owens (1998), von Schantz *et al.* (1999), and Møller *et al.* (2000) kick-started a new era in research on animal pigmentation, antioxidants and signalling. It certainly was helpful that, at the same time, accessible and repeatable methodologies for assessing total antioxidant capacity (Prior & Cao 1999) and oxidative stress (Finkel & Holbrook 2000) in animals became available. The application of this work to issues in pollution and metal contamination in both aquatic and terrestrial systems (Valavanidis *et al.* 2006; Koivula & Eeva 2010) speaks directly to the ecological breadth and potential of AO and OS tools.

In preparing this 5-paper special feature issue, our aim has been to capture the spirit of these emerging fields and the dedicated efforts to marry mechanistic and functional perspectives to a fundamental challenge for life on Earth – an oxygen-rich environment. First, in a conceptual overview article, Costantini *et al.* (2010) review the history of the field, providing many of the essential biomedical and biochemical details of AO and OS systems, so that ecologists can be firmly grounded in the origins and early advances in the field. Then, Hõrak & Cohen (2010) flesh out many of the statistical and measurement methodologies and challenges for quantifying AOs and OS in wild plant, animal, and fungal systems. Given the emphasis of this journal, these authors highlight the need to identify functional aspects to AO and OS bioassays before they become widespread. Following these two overview papers are three specialized articles that hone in on salient ecological aspects of AOs and OS. Buttemer, Abele & Costantini (2010) evaluate the evidence that OS and AOs influence longevity in free-ranging organisms, paying special attention to the influences of body size and metabolic rate, for example. Metcalfe & Alonso-Alvarez (2010) examine the degree to which oxidative stress constrains life-history evolution and emphasize how developmental trajectories (including maternal effects), sexual traits, mate selection and senescence are among the most commonly shaped characteristics by OS demands. Finally, Cohen, de Magalhães & Gohil (2010) sift through the extensive pharmacology and epidemiology literature on AOs and OS, to glean approaches and patterns that are more appropriate *and* most problematic for ecologists.

Despite the emerging excitement over antioxidant and oxidative-stress ecology and the wealth of information from which we can now draw, many challenges lie ahead for these fields. Most glossaries in general biology textbooks still lack the keywords 'antioxidant' and 'oxidative stress' (K. J. McGraw, pers. obs.), symbolic of how specialized these fields are still perceived to be and of the lack of generated interest and understanding from the beginning of most biologist's careers. Even among enthusiasts, there is initial disagreement about the proper sampling schemes to use, metrics to obtain, and assays to run that capture proper AO functions and balances relative to OS demands (Costantini & Verhulst 2009). Indeed, many of the papers published so far on free-living animals suffer from methodological problems, and even the conceptual issues, such as functional definitions of OS, damage and oxidative balance systems, are still open for discussion. Initial taxonomic biases (i.e. birds; Costantini & Møller 2008; Costantini 2008; Cohen *et al.* 2008) may also hinder our ability to make broad generalizations about AOs and OS and uncover unique adaptations and trade-offs.

In sum, it has been a fruitful first decade of life for AO and OS ecology. We hope that readers find this Special Feature issue in *Functional Ecology* both timely and useful, in contextualizing historical bodies of research and in stimulating new directions and research collaborations for years to come.

## Acknowledgements

During manuscript and special feature preparation, KJM was financially supported by the National Science Foundation (grant no's: IOS-0746364 and -0923694), the College of Liberal Arts and Sciences and the School of Life Sciences at Arizona State University, and by an Erskine sabbatical fellowship through the University of Canterbury (Christchurch, New Zealand). DC was supported by a NERC postdoctoral research fellowship (NE/G013888/1). PH was financed by Estonian Science Foundation grant no. 7737, the Estonian Ministry of Education and Science (target-financing project no. 0180004s09) and by the European Union through the European Regional Development Fund (Center of Excellence FIBIR).

## References

Buttemer, W.A., Abele, D. & Costantini, D. (2010) From bivalves to birds: oxidative stress and longevity. *Functional Ecology*, **24**, 971–983.

Cohen, A.A., de Magalhães, J.P. & Gohil, K. (2010) Ecological, biomedical, and epidemiological approaches to understanding oxidative balance and aging: what they can teach each other. *Functional Ecology*, **24**, 997–1006.

Cohen, A.A., McGraw, K.J., Wiersma, P., Williams, J.B., Robinson, W.D., Robinson, T.R., Brawn, J.D. & Ricklefs, R.E. (2008) Interspecific associations between circulating antioxidant levels and life-history variation in birds. *American Naturalist*, **172**, 178–193.

Costantini, D. (2008) Oxidative stress in ecology and evolution: lessons from avian studies. *Ecology Letters*, **11**, 1238–1251.

Costantini, D. & Møller, A.P. (2008) Carotenoids are minor antioxidants for birds. *Functional Ecology*, **22**, 367–370.

Costantini, D. & Verhulst, S. (2009) Does high antioxidant capacity indicate low oxidative stress? *Functional Ecology*, **23**, 506–509.

Costantini, D., Rowe, M., Butler, M.W. & McGraw, K.J. (2010) From molecules to living systems: historical and contemporary issues in oxidative stress and antioxidant ecology. *Functional Ecology*, **24**, 950–959.

Engel, S., Lease, H.M., McDowell, N.G., Corbett, A.H. & Wolf, B.O. (2009) The use of tunable diode laser absorption spectroscopy for rapid measurements of the $\delta^{13}C$ of animal breath for physiological and ecological studies. *Rapid Communications in Mass Spectrometry*, **23**, 1281–1286.

Finkel, T. & Holbrook, N.J. (2000) Oxidants, oxidative stress and the biology of ageing. *Nature*, **408**, 239–247.

Hõrak, P. & Cohen, A. (2010) How to measure oxidative stress in an ecological context: methodological and statistical issues. *Functional Ecology*, **24**, 960–970.

Koivula, M.J. & Eeva, T. (2010) Metal-related oxidative stress in birds. *Environmental Pollution*, **158**, 2359–2370.

Lee, K. & Berenbaum, M.R. (1990) Defense of parsnip webworm against phototoxic furanocoumarins: role of antioxidant enzymes. *Journal of Chemical Ecology*, **16**, 2451–2460.

Lee, K. & Berenbaum, M.R. (1993) Food utilization and antioxidant enzyme activities of black swallowtail in response to plant phototoxins. *Archives of Insect Biochemistry and Physiology*, **23**, 79–89.

Metcalfe, N. & Alonso-Alvarez, C. (2010) Oxidative stress as a life-history constraint: the role of reactive oxygen species in shaping phenotypes from conception to death. *Functional Ecology*, **24**, 984–996.

Møller, A.P., Biard, C., Blount, J.D., Houston, D.C., Ninni, P., Saino, N. & Surai, P.F. (2000) Carotenoid-dependent signals: indicators of foraging efficiency, immunocompetence or detoxification ability? *Avian and Poultry Biology Reviews*, **11**, 137–159.

Olson, V.A. & Owens, I.P.F. (1998) Costly sexual signals: are carotenoids rare, risky or required? *Trends in Ecology & Evolution*, **13**, 510–514.

Peterson, B.J. & Fry, B. (1987) Stable isotopes in ecosystem studies. *Annual Review of Ecology and Systematics*, **18**, 293–320.

Porter, W.P., Mitchell, J.W., Beckman, W.A. & DeWitt, C.B. (1973) Behavioral implications of mechanistic ecology. *Oecologia*, **13**, 1–54.

Prior, R.L. & Cao, G. (1999) *In vivo* total antioxidant capacity: comparison of different analytical methods. *Free Radical Biology and Medicine*, **27**, 1173–1181.

von Schantz, T., Bensch, S., Grahn, M., Hasselquist, D. & Wittzell, H. (1999) Good genes, oxidative stress and condition-dependent sexual signals. *Proceedings of the Royal Society of London, Series B, Biological Sciences*, **266**, 1–12.

Sterner, R.W. & Elser, J.J. (2002) *Ecological Stoichiometry: The Biology of Elements from Molecules to the Biosphere*. Princeton University Press, Princeton, NJ.

Valavanidis, A., Vlahogianni, T., Dassenakis, M. & Scoullos, M. (2006) Molecular biomarkers of oxidative stress in aquatic organisms in relation to toxic environmental pollutants. *Ecotoxicology and Environmental Safety*, **64**, 178–189.