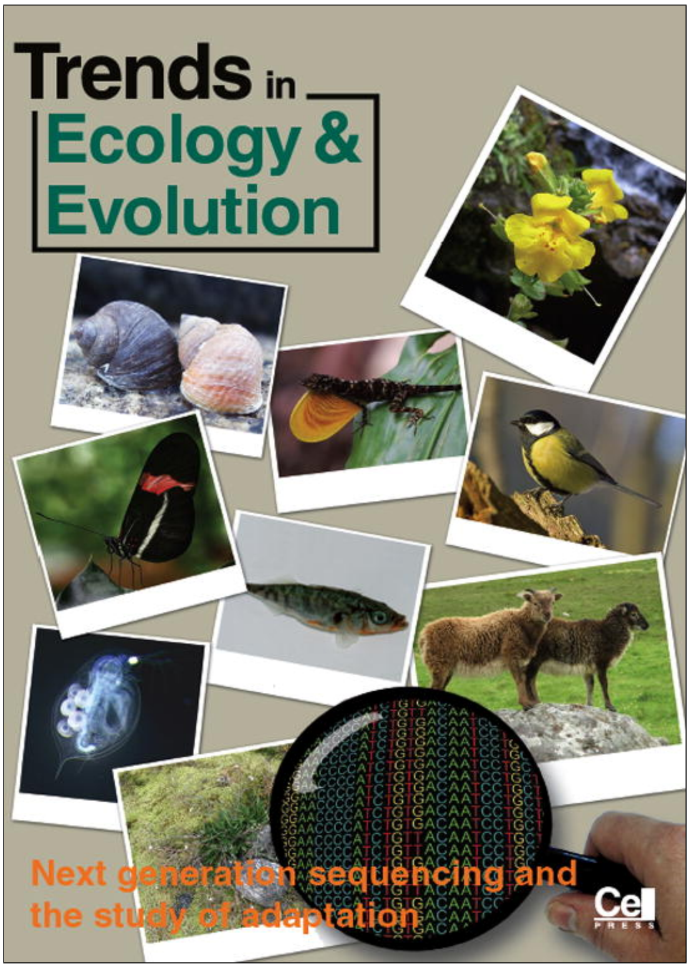
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see an urgent need to prioritize research, and to inform policy development and strategic planning.

Acknowledgements

We are grateful to Michael Monaghan and Gernot Glöckner for helpful comments and to Peter Kappeler and Christian Voigt for information on primates and bats. This work was supported by the project 'Verlust der Nacht' (funded by the Federal Ministry of Education and Research), Milieu (FU Berlin) and the Senatsverwaltung für Bildung, Wissenschaft und Forschung, Berlin.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tree.2010.09.007.

References

1 Sutherland, W.J. *et al.* (2010) A horizon scan of global conservation issues for 2010. *Trends Ecol. Evol.* 25, 1–7

2 Smith, M. (2009) Time to turn off the lights. *Nature* 457, 27

3 Hölker, *et al.* (2010) The dark side of light - a transdisciplinary research agenda for light pollution policy. *Ecol. Soc.* 15

4 Dunlap, J.C. (1999) Molecular bases for circadian clocks. *Cell* 96, 271–290

5 Menaker, M. *et al.* (1997) Evolution of circadian organization in vertebrates. *Braz. J. Med. Biol. Res.* 30, 305–313

6 Bowmaker, J.K. (2008) Evolution of vertebrate visual pigments. *Vision Res.* 48, 2022–2041

7 Rich, C. and Longcore, T., eds (2006) *Ecological Consequences of Artificial Night Lighting*, Island Press

8 Carpenter, S.R. *et al.* (2009) Science for managing ecosystem services: beyond the Millennium Ecosystem Assessment. *Proc. Nat. Acad. Sci. U. S. A.* 106, 1305–1312

9 Potts, S.G. *et al.* (2010) Global pollinator declines: trends, impacts and drivers. *Trends Ecol. Evol.* 25, 345–353

10 Hendry, A.P. *et al.* (2010) Evolutionary biology in biodiversity science, conservation, and policy: a call to action. *Evolution* 64, 1517–1528

11 Alfaro, M.E. *et al.* (2009) Nine exceptional radiations plus high turnover explain species diversity in jawed vertebrates. *Proc. Nat. Acad. Sci. U. S. A.* 106, 13410–13414

12 Bininda-Emonds, O.R.P. *et al.* (2007) The delayed rise of present-day mammals. *Nature* 446, 507–512

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Letters Response

Swarm intelligence in plant roots

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Swarm intelligence in animals and humans has recently been reviewed [1]. These authors posited that swarm intelligence occurs when two or more individuals independently, or at least partly independently, acquire information that is processed through social interactions and is used to solve a cognitive problem in a way that would be impossible for isolated individuals. We propose at least one example of swarm intelligence in plants: coordination of individual roots in complex root systems.

Plants develop extremely complex root systems, which colonize large soil areas. For example, calculations for one winter rye plant revealed 13 815 672 roots with a surface area of about 130 times that calculated for shoots [2]. Growing root apices show complex behaviour based on 'intelligent' decisions about their growth directions [3,4]. Moreover, growing roots show coordinated group behaviour that allows them to exploit the soil resources optimally. There are three possible communication channels for context-dependent information transfer among the numerous root apices of the same plant. Firstly, neuronal-like networks within plant tissues that support rapid electrical and slower hydraulic and chemical information transfer between the root apices [5,6]. Secondly, secreted chemicals and released volatiles allow rapid communication between individual roots. Thirdly, there is a possibility that the electric fields generated by each growing root [7] might allow electrical communication among roots. These electric activities and electric fields show maximal values [7,8] at the transition zone of growing root apices [3] which behaves as a 'brain-like' command centre [6,9]. Roots may use swarm intelligence for their navigation, coordination, cooperation, as well as for their 'war-like' aggressions [10]. It is important that every root has its own identity provided by its unique sensory history accumulated via its own command centre. Each root apex acts both as a sensory organ and as a 'brain-like' command centre to generate each unique plant/root-specific cognition and behaviour [3,6,9]. Recent advances in the emerging field of sensory plant ecology suggest that the sensory information collected by one plant is shared with neighbouring plants [11,12]. In the case of root apices, sensory information appears to be processed collectively in the root system to optimize root-mediated territorial activities [13–16]. These root apices solve cognitive problems such as where to grow and whether to grow at all, to fight or retreat in a face of competitive roots and root systems [10] and to enter symbiotic relationships with mycorrhiza fungi (and *Rhizobium* bacteria in the case of some species) [3–6,13–15]. So roots enjoy a rich 'social' life at the individual plant level and they continuously solve problems that could be called cognitive [4,13]. Swarm intelligence is essential for the evolutionary success of roots and, consequently, the whole plant. The accumulating data on the

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complicated and sophisticated integration of the root community at the individual plant level described above composes the basic level on top of which similar integrated actions occur at the group level. The fact that certain plant species are able to distinguish between self and non-self roots [13–16] helps plants to integrate the mutual self- and non-self signals for decisions at the community level to invest more or less in root growth towards resources, in communication, or in chemical defences according to neighbour relatedness. Thus, plants acquire information through and within their root system, which is processed through social interactions and which provides solutions to cognitive problems that are not available to isolated individuals, allowing them to better exploit and survive in the three-dimensional, competitive and hazardous dark underground world.

It emerges that the swarm intelligence does not have to be restricted to animals. Plants can learn and remember through epigenetic modifications and biochemical processes [13,17]. Moreover, the concepts of plant intelligence, memory, behaviour and cognition are elaborated and prove to be relevant for higher plants [5,13; but see also 18,19]. In conclusion, the swarm intelligence concept should be considered as a working hypothesis for plants until enough theoretical analyses and experimental data accumulate to dismiss or accept it concerning adaptive plant behaviour.

References

1 Krause, J. *et al.* (2010) Swarm intelligence in animals and humans. *Trends Ecol. Evol.* 25, 28–34
2 Dittmer, H.J. (1937) A quantitative study of the roots and root hairs of a winter rye plant (Secale cereale). *Am. J. Bot.* 24, 417–420
3 Baluška, F. *et al.* (2010) Root apex transition zone: a signalling - response nexus in the root. *Trends Plant Sci.* 15, 402–408
4 Hodges, A. (2009) Root decisions. *Plant Cell Environ.* 32, 628–640
5 Brenner, E.D. *et al.* (2006) Plant neurobiology: an integrated view of plant signaling. *Trends Plant Sci.* 11, 413–419
6 Baluška, F. *et al.* (2009) The 'root-brain' hypothesis of Charles and Francis Darwin: Revival after more than 125 years. *Plant Signal. Behav.* 4, 1121–1127
7 Collings, C.A. *et al.* (1992) Ionic current changes associated with the gravity-induced bending response in roots of *Zea mays* L. *Plant Physiol.* 100, 1417–1426
8 Masi, E. *et al.* (2009) Spatio-temporal dynamics of the electrical network activity in the root apex. *Proc. Natl. Acad. Sci. U. S. A.* 106, 4048–4053
9 Baluška, F. *et al.* (2004) Root apices as plant command centres: the unique 'brain-like' status of the root apex transition zone. *Biologia* 59, 9–17
10 Novoplansky, A. (2009) Picking battles wisely: plant behaviour under competition. *Plant Cell Environ.* 32, 726–741
11 Schenk, H.J. and Seabloom, E.W. (2010) Evolutionary ecology of plant signals and toxins: a conceptual framework. In *Plant Communication from an Ecological Perspective* (Baluška, F. and Ninkovic, V., eds), Springer-Verlag, Berlin, pp. 1–19
12 Heil, M. and Karban, R. (2010) Explaining evolution of plant communication by airborne signals. *Trends Ecol. Evol.* 25, 137–144
13 Trewavas, A. (2009) What is plant behaviour? *Plant Cell Environ.* 32, 606–616
14 Callaway, R.M. and Mahall, B.E. (2007) Family roots. *Nature* 448, 145–147
15 Gruntman, M. and Novoplansky, A. (2004) Physiologically mediated self/non-self discrimination. *Proc. Natl. Acad. Sci. U. S. A.* 101, 3863–3867
16 Biedrzycki, M.L. *et al.* (2010) Root exudates mediate kin recognition in plants. *Commun. Integr. Biol.* 3, 28–35
17 Jablonka, E. and Raz, G. (2009) Transgenerational epigenetic inheritance: prevalence, mechanisms, and implications for the study of heredity and evolution. *Q. Rev. Biol.* 84, 131–176
18 Firn, R. (2004) Plant intelligence: an alternative point of view. *Ann. Bot.* 93, 345–351
19 Alpi, A. *et al.* (2007) Plant neurobiology: no brain, no gain? *Trends Plant Sci.* 12, 135–136

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Book Review

Astrobiology in Antarctica

Life in Antarctic Deserts and other Cold Dry Environments by Peter Doran, W. Berry Lyons and Diane McKnight. Cambridge University Press, 2010. US$110.00/£65.00 hbk (320 pages) ISBN 978 0 521 88919 3

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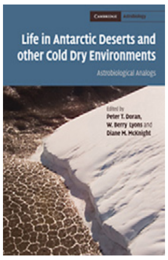

Of the many discoveries and trends that have emerged in our understanding of life in extreme environments on Earth, there can be little doubt in saying that the convergence of polar biology and planetary sciences has been one of the most fruitful and insightful. It has led biologists to other worlds. Space missions are expensive, but recent high resolution cameras and new, sophisticated analytical instruments have continued to support the idea that the planet Mars had, and indeed still has, environments that come close in their physical and chemical extremes to Earth's polar regions.

In this multi-authored volume written by three of the main protagonists of the debate about the similarities and dissimilarities between polar environments and Mars, we are provided with a wealth of data and discussions about different angles of this work. The editors, having made significant contributions to this field themselves, have been able to put together an outstanding book.

Amongst other polar environments, the Dry Valleys of Antarctica, which harbour perennially ice-covered lakes and periglacial features similar to those observed on Mars, are explored in Chapter 2, after a very interesting and readable history of this area of research in the first chapter.

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