CSIRO PUBLISHING

RESEARCH FRONT

Marine and Freshwater Research, 2016, **67**, 391–392
http://dx.doi.org/10.1071/MF15330

Editorial

New diagnostics for multiply stressed marine and freshwater ecosystems: integrating models, ecoinformatics and big data

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Received 25 August 2015, accepted 31 August 2015, published online 22 October 2015

It is now a truism to state that the Earth is under threat from pervasive human activity, and that we have entered a new era of accelerating planetary change: The Anthropocene (Steffen *et al.* 2011). The convergent development of earth-observation systems, coupled with high-performance computing platforms linked through the internet have revealed the fragile state of the biosphere at a critical tipping point in terms of the preservation of biodiversity and its associated ecosystem services (Barnosky *et al.* 2012). The diverse habitats present in aquatic ecosystems – the Earth's oceans, coasts, lakes and rivers – are under imminent threat from a variety of human-induced, interconnecting stressors arising from a changing climate, associated sea-level rise, alterations to the global water cycle and the consequences of globalised trade (Liu *et al.* 2015). There is now general recognition that environmental problems require complex solutions, and that observing and understanding ecological change in aquatic ecosystems cannot ignore the issue of multiple causality arising from complex stress regimes (e.g. Jackson *et al.* 2016). Against this background, a workshop was held from 10 to 12 September in 2014 at the Sydney Institute of Marine Sciences in Sydney, NSW. Working groups of scientists from a diversity of backgrounds and disciplines explored three key aspects of multiple-stressor impacts on aquatic ecosystems: (1) defining stressors at ecosystem scale using knowledge of the temporal and spatial scaling of stressor effects and exploring the role of geospatial data in stressor mapping; (2) new technologies for the acquisition of effects data and the development of diagnostics in complex ecosystem-stressor scenarios, including genomics, modelling and statistical tools; and (3) how new technologies and approaches for large-scale ecosystem assessment can be employed in the regulatory arena, to link assessments from headwaters to open oceans in ecological risk assessment (ERA).

The Driver–Pressure–State–Impact–Response framework developed by the European Environment Agency (Smeets and Weterings 1999) was chosen as a suitable heuristic model for multiple-stressor impacts at ecosystem scale, providing a focus for the resulting workshop outputs. Fig. 1 illustrates the linkages and pathways by which environmental 'drivers', resulting from a combination of anthropogenic activity and natural variability, result in the action of 'pressures' (here, and in the workshop papers, pressures is synonymous with stressors) on ecosystem 'state' (e.g. the habitat template, biodiversity). This in turn causes 'impacts' which can be observed as ecosystem trends, leading to degradation and, ultimately, ruin (*sensu* Taleb *et al.* 2014). Ecosystem 'responses' are observed in terms of their capacities to return to a previous state (resilience or antifragility) or their tendency to collapse (fragility) *sensu* Taleb (2014).

The first paper in the workshop series by Dafforn *et al.* (2016) focuses on two critical issues in multiple-stressor ecology: (*i*) developing a conceptual framework for study, which takes into account issues of spatial and temporal scaling in relation to the DPSIR framework; and, (*ii*) the availability of suitable data, including 'big data' sources, which can provide information on Driver–Pressure–State relationships. Their paper includes a brief critique of existing multiple-stressor approaches, which are largely *ad hoc* and expert knowledge-driven, and thus suffer from a lack of formal rigour, and provide a poor model for a multiple-stressor paradigm, which should be extendable from ecosystem to planetary scale. The second paper, by Chariton *et al.* (2016), outlines a formal structure to align existing and emerging

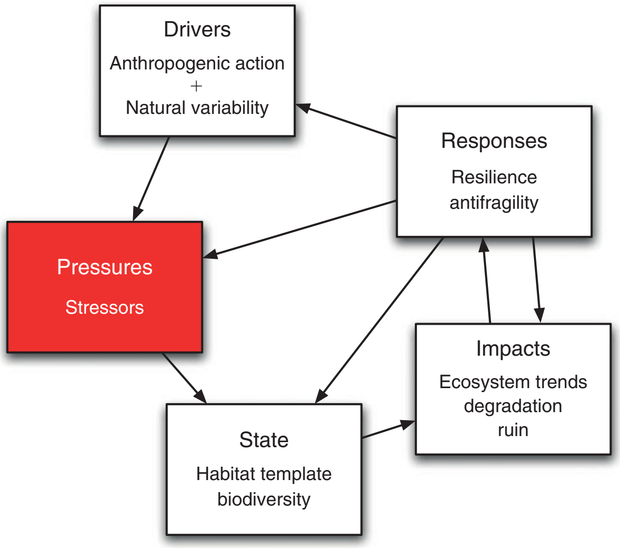

Fig. 1. The Driver–State–Pressure–Impact–Response (DPSIR) framework adapted to represent the impacts on natural ecosystems caused by multiple stressors, arising from anthropogenic activity (after Smeets and Weterings 1999).

technologies in ecosystem observation and stress ecology to develop new diagnostics for marine- and freshwater-ecosystem monitoring and assessment. In particular, several emerging technologies, including environmental genomics and new statistical approaches are explored in detail, and their integration in a formal ecological-risk-assessment framework is illustrated. Chariton *et al.* (2016) highlight the use of new statistical approaches for causal inference, including Bayesian networks, concluding that a variety of modelling approaches are needed to allow flexibility for interpretation of complex causality chains within natural ecosystems under stress. In the third paper, Van den Brink *et al.* (2016) confront the challenge of integrating new, multi-scale and big-data approaches within a regulatory ERA framework. They view this opportunity as the basis to develop a new paradigm for ERA, which allows a global approach to be taken, yet permits the development of scaleable regulatory guidelines, driven by availability of localised models and data.

Together, these papers offer a start for a new program of research, focusing on the integrated assessment of the Earth's aquatic ecosystems. This program explicitly recognises that marine and freshwater ecosystems are interconnected, and that no matter what spatial or temporal level of impact is of concern, drivers and pressures operating at all levels of organisation must be considered when determining cause. This will not be a simple task, but it is now clear that we possess the necessary tools to achieve it. It is our hope that the papers described above can provide inspiration for new research projects and the basis of a path forward for regulators, and other stakeholders, to implement change across their environmental management and monitoring programs.

Acknowledgements

The authors thank the CSIRO Oceans and Atmosphere Flagship, Sydney Institute of Marine Science and the New South Wales Office of Environment and Heritage for their financial support of the workshop 'New diagnostics for multiply stressed marine and freshwater systems: integrating models, ecoinformatics and big data'. E. L. Johnston and K. D. Dafforn acknowledge support from the Australian Research Council's Linkage Grant Program. D. J. Baird acknowledges support from the Natural Sciences and Engineering Research Council of Canada's Discovery Grant program, a Distinguished Visiting Scientist award from the Commonwealth Science and Industry Research Organisation of Australia, and a Distinguished Visitors Fellowship Award from University of New South Wales in the development and delivery of this workshop.

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