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Supplementary material

New approaches to the ecological risk assessment of multiple stressors

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Case studies

Case study 1: using big data in risk assessments of the Great Barrier Reef

Poor water quality from nutrients, sediment and pesticides in terrestrial runoff is a major management issue for the Great Barrier Reef (GBR), particularly in the face of climate change (Wooldridge and Done 2009; Brodie *et al*. 2013). Studies have demonstrated the link between poor water quality and decreased capacity of the reef to recover after natural disturbances such as cyclones and crown-of-thorn starfish (Fabricius and De'Ath 2004). Management of the GBR would greatly benefit from an ecological risk-assessment model capable of using 'big data' and multiple line-of-evidences to account for (1) its large scale, (2) its complex network of ecosystems and food webs, (3) the multiple anthropogenic and natural stressors, (4) the spatial and temporal variability of those stressors, (5) the fate of contaminants as they move from catchments to coastal and marine ecosystems, and last, (6) the interactions among the stressors. In addition, ecological risk assessments for the GBR also need to account for the regional management boundaries, and the cultural and economic values influencing management objectives, such as, e.g. the GBR's World Heritage Status, the high growth in development for the adjacent State of Queensland, economic benefits of tourism and fisheries, and the indigenous cultural significance of the reef.

The Reef Water Quality Protection Plan (eReefs, see http://www.ereefs.org.au/, accessed 19 September 2014) was established to manage the degraded water transported to the reef to ensure the health and resilience of the GBR to climate-change stressors. The investment from the Australian and Queensland governments allocated to generating empirical datasets, water-quality monitoring and modelling of agricultural runoff to the GBR has led to a large body of data, from the receptor scale (e.g. Flores *et al*. 2013) to the landscape scale (e.g. Devlin and Schaffelke 2009). The most recent ecological risk assessment conducted for the GBR involved a large-scale assessment of the risks of nutrients, sediments and pesticides to the reef. Using a line-of-evidence and weight-of-evidence approach, the risk assessment was described as 'the first step in prioritising management focused on the regional 'hot spots' of pollutant sources…' (Brodie *et al*. 2013). However, several limitations were noted that could be overcome with additional data and use of mechanistic or empirical ecological models. Limitations included the temporal and spatial resolution of the input datasets, variability in the spatial resolution of the datasets, the cumulative impacts and interactions of stressors, the environmental relevance of the risk metrics and weighting of stressors, and the cultural and economic values of the GBR (Brodie *et al*. 2013).

As the reef plan progresses, the body of data available for the parameterisation and evaluation of ecological models and stressor response is set to increase. In the past, these data have been stored in separate areas with different governing agencies, universities and other research organisations, making it difficult to pool the data together for the purpose of ecological modelling and risk assessments. In 2012, eReefs, a collaborative project among government, industries and managers, was established to collate and centralise these data to build a comprehensive coastal information system for the benefit of managing the GBR (eReefs 2014, see http://www.ereefs.org.au/). In doing so, achieving a comprehensive model to evaluate the current risks of multiple stressors on the GBR and to predict the interaction of poor water quality with climate change is foreseeable.

Case study 2: using ecological models for assessing the risk of multiple stressors in New South Wales, Australia, estuaries

The State of New South Wales (NSW) has 184 estuaries, with a range of forms from large rivers to small intermittently open coastal lagoons and streams. In 180 of these, the primary stressors are not toxicants, but nutrients, turbidity and salinity (Scanes *et al*. 2007). Models of the consequences of land use for these stressors, and their impacts on primary producers in estuaries, have been constructed for all NSW estuaries. The models are informed by research on critical ecosystem processes (e.g. nutrient cycling in sediments, response to nutrient additions, factors controlling sea-grass growth) and a comprehensive estuary-condition monitoring program. The models utilise integrated catchment, hydrodynamic and ecological response submodels. They have been implemented at two scales, namely, simple empirical ecological models predicting chlorophyll concentrations from input nutrient loads, and potential seagrass cover from input sediment loads that have been developed for all 184 estuaries (Sanderson and Coade 2010; http://www.ozcoasts.gov.au/nrm_rpt/cerat/index.jsp, accessed 1 December 2015). These models empirically integrate consequences of multiple stressors (nutrients, sediments, salinity) with modifying factors (estuary type, entrance condition, runoff volume), to provide a relative risk assessment for catchment land-use scenarios. Secondary benefits of the state-wide program have included an estuarine typology, the derivation of a catchment disturbance index, calculation of the value of the estuary type-specific guidance criteria for chlorophyll and turbidity (as integrated indicators) and nutrient species (as measures of stressors).

In more intensively studied estuaries, significantly more detailed and spatially explicit mechanistic and empirical ecological models coupled to detailed catchment and hydrodynamic models have been constructed. This is to provide managers with an assessment of consequences of catchment land-use change and to identify the most effective sites for management intervention. Again, these models are based on extensive research into critical ecological processes.

The adaptive management cycle is completed through a state-wide estuary-monitoring program that uses as indicators, the same factors as predicted by models (e.g. chlorophyll and turbidity), facilitating the verification of models and evaluation of managerial decisions.

Case study 3: multiple-stressor risk assessment of the Magela Creek Floodplain, Kakadu National Park, Australia (based on Bayliss et al. *2012)*

The Ranger Uranium mine is located in the Northern Territory, Australia, and is surrounded by areas of high ecological and cultural significance, namely, the World Heritage-listed Kakadu National Park and the Magela Creek floodplain, a designated Ramsar wetland. The ecological and cultural values of the area require the mine to operate under strict environmental regulation and scrutiny. In addition to the mine, the Magela Creek floodplain is exposed to other ecological threats such as invasive species, unmanaged late dry-season fires and climate change. The Kakadu Plan of Management (2007–2014) identified that ecological threats had not been examined in an 'integrated monitoring and risk-assessment framework' similar to the approach adopted to monitor and manage impacts from the mine site. A quantitative ecological risk assessment (QERA) was therefore conducted, combining both point-source mining risks (four key mine-derived contaminants: uranium, manganese, magnesium and sulfate) and diffuse non-mining landscape-scale risks (weeds, feral pig damage, unmanaged dry season fire, and saltwater intrusion from potential sea-level rise as a result of climate change). Water quality-monitoring data were combined with species sensitivity distributions, wetland vegetation-mapping data, a bioeconomic model for weed management, aerial-survey data of ground disturbance from feral pigs, 25 years of Landsat-based fire-scar maps, estimates of sea-level rise and geographical spatial data. The ecological risk assessment involved a three-step process, as follows: (1) the individual and combined ecological risks from the mine site and landscape were quantified using probability density functions fitted to exposure and effects data; (2) a Monte Carlo simulation was applied to account for model uncertainty; and (3) to facilitate communication of the QERA results to stakeholders for decision-making purposes, a Bayesian belief network was employed. Through this method, it was concluded that non-mining landscape-scale risks to the floodplain were several orders of magnitude greater than were risks from mine water contaminants. The invasive aquatic weed, para grass, was found to be the major ecological risk to the floodplain through its displacement of native vegetation and wildlife habitat. Unmanaged dry-season fires followed by feral pig damage posed the next greatest risks above mine water contaminants. This example provides evidence of the importance of estimating combined risks and why landscape-scale risks should receive the same level of close scrutiny and investment as that applied to contaminant risks.

Case study 4: ecological risk assessment in an urban setting, using the relative risk model

The management of important ecological services is often necessary within urban settings. Hines and Landis (2014) used ecological risk assessment to estimate risk from multiple stressors to the regionally iconic coho salmon in the Puyallup River. The Puyallup River flows from Mount Rainier National Park to the Port of Tacoma, one of the largest on the western coast of North America (Fig. S1). There is a clear gradient of urbanisation from the protected areas surrounding Mount Rainer National Park (Regions 1 and 2) that are used for recreation, forestry and agriculture. Regions 3 and 4 are increasing in urbanisation, with a great deal of commercial and residential land use, manufacturing activity and transportation corridors. Region 5 is the Port of Tacoma, a large container-ship facility that also includes a paper mill, manufacturing, and a waste-treatment plant. Region 6 is primarily the city of Tacoma, with a high population density, a sports and convention centre and universities.

In this case study, the endpoint was specifically the occurrence of pre-spawner mortality (PSM) to coho salmon (*Oncorhynchus kisutch*). PSM occurs in fish as they move upstream to spawn and has a very specific symptomology. Coho salmon is one of the iconic fish of the region and spawns throughout the Puget Sound. Pre-spawn mortality has been observed in several river systems in the region following large storm events. The other critical factor is that the study of Hines and Landis (2014) also examined the potential of low-impact development (LID), commonly called green infrastructure, as a potential management tool to decrease the risk of PSM in the watershed. The estimation of risk was calculated using the Bayesian network derivation of the relative risk model (BN-RRM).

A conceptual model was used to show the causal pathways for the risk posed to the coho population caused by PSM. Pre-spawn mortality in this model is represented by the effect caused by stormwater and contaminants in stormwater runoff from specific land use. Specifically, commercial property, roads, and other impervious surfaces were used as the three land-use types assumed to contribute the contaminants responsible for PSM and are used here as predictors (Spromberg and Scholz 2011). The link to roads and other impervious surfaces implies that motor vehicles and a mixture of heavy metals and polycyclic aromatic hydrocarbons (PAHs) are likely to be linked to PSM (Scholz *et al*. 2011). Coho migratory habitat and observed escapements are also incorporated into the model to demonstrate the likelihood that coho will encounter an overlap and exposure with the stressors that cause PSM. LID is incorporated into the model as a filter that reduces contaminants and stormwater runoff within a watershed.

The conceptual model is the framework for the construction of the Bayesian network that describes in a probabilistic fashion the interactions among the various contaminants, the landscape, the occurrence of PSM and the potential risk to coho salmon. The BN-RRM was parameterised using a combination of spatial analysis data, empirical data from published and state government data, and expert judgment gathered from published reports. Conditional probability tables describing the casual relationships were developed to reflect our current knowledge and the uncertainty. Parameters include land use, frequency of large stormwater events, the occurrence of LID in the risk regions, the filtering ability of LID, coho migratory habitat, the status of the coho population and PSM.

The distribution of risk in the watershed is illustrated in Fig. S1. The gradient is from east to west, with the highest risk regions corresponding to the urban and industrial areas in Regions 5 and 6. Land use was a critical variable as determined by the sensitivity analysis. Once the pattern of risk was determined, the next step was to evaluate the ability of LID to reduce the risk.

The impact of LID on the risk estimates was evaluated for each region. An increase in LID did decrease risk. The greatest risk reduction was in the most developed regions, namely Regions 3, 5 and 6. That does not mean that LID can easily reduce risk to the level seen in the less developed areas of

Regions 1 and 2. As an example in a simulation, the amount of LID in Region 5 (region at highest risk) was increased to 41% of the landscape. Although the risk was decreased, it was still above that of Regions 1 and 2 without LID. Even with the extensive application of LID as a management tool, it has proven difficult to reduce the risk in the urban regions.

This case study demonstrated two critical aspects of the use of risk assessment with multiple stressors at a regional or landscape scale. First, it is clearly possible to estimate patterns in risk within a substantial landscape with several sources of contaminants and other stressors. The second is that risk assessment can be used to estimate the utility of a specific management scheme, in this case LID, to accomplish a management goal. In this instance, the analysis indicated that a great deal of the landscape would have to have LID applied to it to reduce risk to the medium category. Such an application would be an integral part of an adaptive management framework.

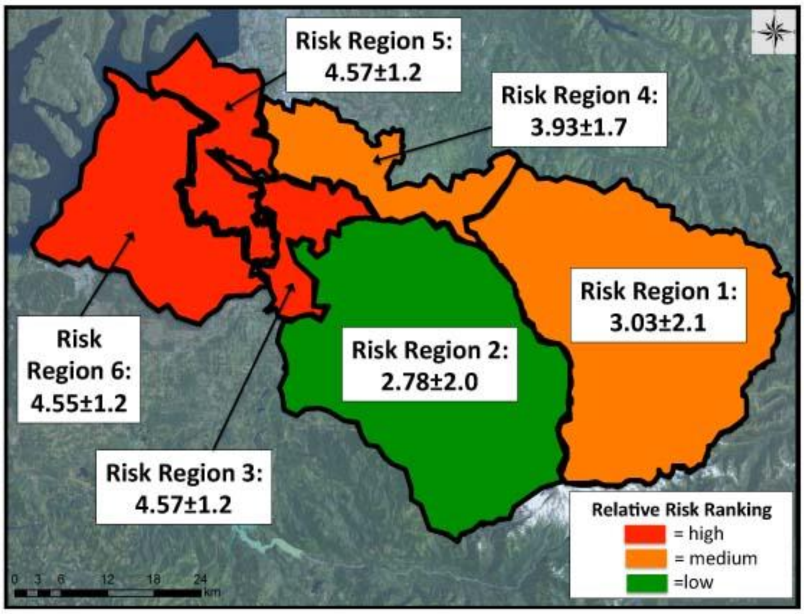

Fig. S1. There is a gradient from the lowest (Region 2) to the highest (Region 5) risk to coho salmon populations as urbanisation increases. The values are means from the Bayesian network derivation of the relative risk model (BN-RRM) distributions, with the calculated standard deviation solely as a measure of uncertainty.

References

Bayliss, P., Van Dam, R. A., and Bartolo, R. E. (2012). Quantitative ecological risk assessment of the Magela Creek Floodplain in Kakadu National Park, Australia: comparing point source risks from the Ranger Uranium Mine to diffuse landscape-scale risks. *Human and Ecological Risk Assessment* **18**, 115–151. doi:10.1080/10807039.2012.632290

Brodie, J., Waterhouse, J., Schaffelke, B., Furnas, M., Maynard, J., Collier, C., Lewis, S., Warne, M. St. J., Fabricus, K., Devlin, M., McKenzie, L., Yorkston, H., Randall, L., Bennett, J., and Brando, V. (2013). 2013 Scientific Consensus Statement. Chapter 3: Relative Risks to the Great Barrier Reef from Degraded Water

Quality. (Reef Water Quality Protection Plan Secretariat: Brisbane.) Available at http://www.reefplan.qld.gov.au/about/scientific-consensus-statement/water-quality-risks.aspx [Verified 1 December 2015].

Devlin, M., and Schaffelke, B. (2009). Spatial extent of riverine flood plumes and exposure of marine ecosystems in the Tully coastal region, Great Barrier Reef. *Marine and Freshwater Research* **60**, 1109–1122. doi:10.1071/MF08343

Fabricius, K. E., and De’Ath, G. (2004). Identifying ecological change and its causes: a case study on coral reefs. *Ecological Applications* **14**, 1448–1465. doi:10.1890/03-5320

Flores, F., Collier, C. J., Mercurio, P., and Negri, A. P. (2013). Phytotoxicity of four Photosystem II herbicides to tropical seagrasses. *PLoS One* **8**, e75798. doi:10.1371/journal.pone.0075798

Hines, E. E., and Landis, W. G. (2014). Regional risk assessment of the Puyallup river watershed and the evaluation of low impact development in meeting management goals. *Integrated Environmental Assessment and Management* **10**, 269–278. doi:10.1002/ieam.1509

Sanderson, B. G., and Coade, G. (2010). Scaling the potential for eutrophication and ecosystem state in lagoons of New South Wales, Australia. *Environmental Modelling & Software* **25**, 724–736. doi:10.1016/j.envsoft.2009.12.006

Scanes, P., Coade, G., Doherty, M., and Hill, R. (2007). Evaluation of the utility of water quality based indicators of estuarine lagoon condition in NSW, Australia. *Estuarine, Coastal and Shelf Science* **74**, 306–319. doi:10.1016/j.ecss.2007.04.021

Scholz, N. L., Myers, M. S., McCarthy, S. G., Labenia, J. S., McIntyre, J. K., Ylitalo, G. M., Laetz, C. A., Stehr, C. M., French, B. L., McMillan, B., Wilson, D., Lynch, K. D., Davis, J. W., and Collier, T. K. (2011). Recurrent die-offs of adult coho salmon returning to spawn in Puget Sound lowland urban streams. *PLoS One* **6**, e28013. doi:10.1371/journal.pone.0028013

Spromberg, J. A., and Scholz, N. L. (2011). Estimating the future decline of wild coho salmon populations resulting from early spawner die-offs in urbanizing watersheds of the Pacific Northwest, USA. *Integrated Environmental Assessment and Management* **7**, 648–656. doi:10.1002/ieam.219

Wooldridge, S. A., and Done, T. J. (2009). Improved water quality can ameliorate effects of climate change on corals. *Ecological Applications* **19**, 1492–1499. doi:10.1890/08-0963.1