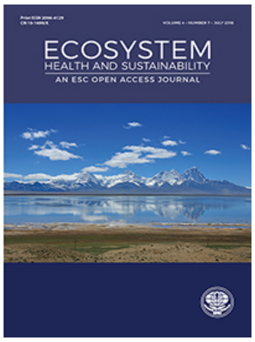

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Interaction between pollution and climate change augments ecological risk to a coastal ecosystem

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ABSTRACT

Pollution and climate change are among the most challenging issues for countries with developing economies, but we know little about the ecological risks that result when these pressures occur together. We explored direct effects of, and interactions between, environmental pollution and climate change on ecosystem health in the Bohai Sea region of Northern China. We developed an integrated approach to assess ecological risks to this region under four scenarios of climate change. Although ecological risks to the system from pollution alone have been declining, interactions between pollution and climate change have enhanced ecological risks to this coastal/marine ecosystem. Our results suggest that current policies focused strictly on pollution control alone should be changed to take into account the interactive effects of climate change so as to better forecast and manage potential ecological risks.

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Climate change; environmental pollution; environmental risk stressors; integrated ecological risk; coastal ecosystem

Introduction

Human activities generate multiple stresses on ecosystems throughout the world, with chemical pollution and climate change being among the most important. Recent research suggests that both pollution and climate change – alone and in combination – are altering the structure, function, and services of ecosystems with consequent reductions in productivity, decreases in biomass, alteration in food-web dynamics, and shifts in species distribution (Karl and Trenberth 2003; Cramer 2006; Scholze, Knorr, and Arnell 2006; Matyssek, Schaub, and Wieser 2010; Backhaus, Snape, and Lazorchak 2012; van Dijk et al. 2012; Brown et al. 2015; Jing et al. 2015). These changes can degrade ecosystems over long time periods and the effects can be difficult to reverse (Grimm et al. 2013; Melissa 2014).

Despite the known interactive effects of pollution and climatic change on ecosystem dynamics, forecasts of risks from these stressors are usually reported independently. To illustrate the combined pressures, however, we focus here on their impacts on marine and coastal ecosystems, which can be severely affected by anthropogenic pollution and climate change (Richardson and Schoeman 2004) with serious consequences likely to remain for decades (Halpern et al. 2008; Post et al. 2009; Hoegh-Guldberg and Bruno 2010). We take as our case study the Bohai Sea region of Northeastern China (Figure 1). The Bohai Sea itself is a nearly enclosed interior sea located in Northeast China bordered by one of the three most densely populated (≈ 4500 inhabitants/km^2) regions in China (NBS, PRC 2015). Most ecosystem services in this region are affected severely by multiple stressors; provisioning services such as fisheries already have been seriously compromised (Kong et al. 2015) (Figure S1).

(ArcMap 10.0, ESRI Inc. http://www.esri.com/software/arcgis)

Pollution and climate change, individually and interactively, are altering biogeochemical cycles in coastal ecosystems such as the Bohai Sea region (Figure 2) and in the open ocean (Smith et al. 2009). For example, increasing atmospheric concentrations of greenhouse gases (CO_2, CH_4, NO_X) are causing ocean acidification, altering carbonate deposition and dissolution patterns of many marine organisms (Jin, Wang, and Liu 2015). Climatic warming is caused by the increased atmospheric concentrations of greenhouse gases; the oceans dominate the increase in stored energy in the climate

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Supplemental data can be accessed here

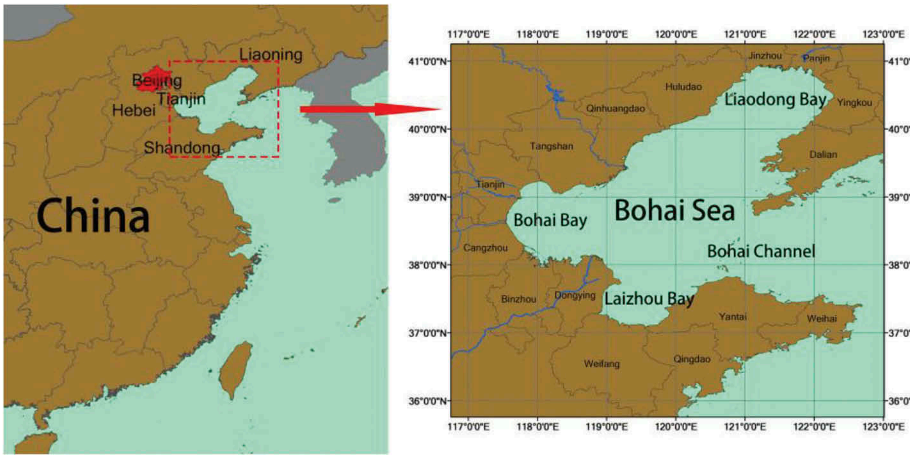

Figure 1. Bohai Sea region of Northeastern China.

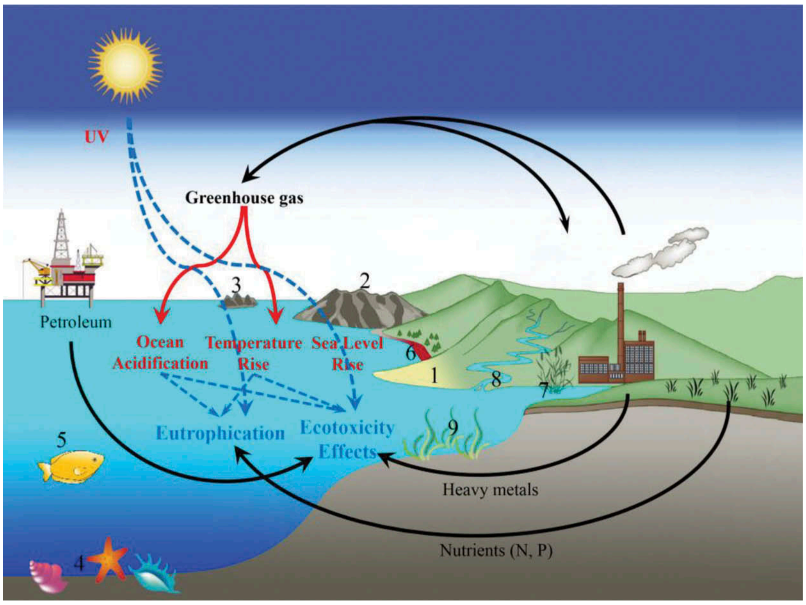

Figure 2. Coastal ecosystems impacted by pollution (black) and climate change (red). Black and red arrows indicate effects of pollution and climatic change, respectively; blue arrows illustrate interconnections among ocean biogeochemical processes. The numbers refer to the nine major ecosystem types in our study area, ordered by risk (1 = highest; 9 = lowest) from interactions between pollution and climatic change from high to low (1: Sandy intertidal; 2: Rocky intertidal; 3: Rocky reef; 4: Benthos; 5: Sea water; 6: Salt marsh (seep-weed beach); 7: Intertidal mud (reed marsh); 8: Estuarine zone; 9: Seagrass bed).

system and account for > 90% of the global energy accumulated between 1971 and 2010 (IPCC 2014). Oceanic warming is a likely cause of the expansion of low-chlorophyll and low-productivity of gyres in the open ocean (Behrenfeld et al. 2016). Anthropogenic pollutants, including heavy metals and petroleum hydrocarbons (PHs), may further decrease photosynthetic rates and increase respiration rates of phytoplankton and algae (Zeng, Chen, and Zhuang 2015), taxa that are considered to be among the most sensitive to environmental stressors (Taylor, Fletcher, and Raven 2001; Taylor et al. 2012). In an unfortunate positive feedback, ocean acidification can increase the biotoxicity of heavy metals by altering their speciation and bioavailability.

Material and methods

Multiple stressors in study area

Local pollution pressure on the Bohai Sea and its coastal region includes discharge of hundreds of millions of tons of untreated industrial wastewater (SOA, PRC 2015), which results in high concentrations of dissolved inorganic nitrogen (DIN), soluble reactive phosphorous (SRP), PHs, and heavy metals (Peng et al. 2009; Li et al. 2010; Peng 2015) including lead (Pb), cadmium (Cd), and mercury (Hg) (Xu et al. 2013; Luo et al. 2012). Among the three heavy metals, Pb contributes a significant risk (Table S11) and so was selected to represent the overall contribution of the heavy metals in the Bohai Sea for further risk analysis. We used concentrations of

DIN, SRP, PHs, and Pb as a heavy metals exemplar, as our measures of pollutant stress.

Although pollution stressors were determined locally, climate-change stressors were related to global drivers. For most of the significant influences on the Bohai coastal area, our measures of stress resulting from climatic change were sea-surface temperature (SST), pH, and UV-B radiation. The global average temperature of surface sea has increased by 0.6°C over the past 100 years (IPCC. 2007). Regional SST in the Bohai Sea has increased by 0.015°C/a from 1960 to 2010 (Figure S5). The absorption of anthropogenic CO_2 has acidified the ocean, with a steady decrease of 0.02 pH units per decade for surface water over the past 30 years (Doney et al. 2009, 2012). Although the signing of the Montreal Protocol in 1987 and its recent amendments have led to some recovery of stratospheric ozone concentrations (Hegglin et al. 2015), lowered concentrations of stratospheric ozone continue to affect ecosystem processes: a 2% reduction in ozone concentration corresponds to a 4% increase in biologically active UV-B flux at the Earth's surface (Oppenheimer 1989). Sea-level rise is also one of the significant climate-change stressors for coastal ecosystem risk. The global average sea-level rise was 3.2 mm/yr between 1993 and 2010 (IPCC 2014).

Integrated risk model

Anthropogenic activities have caused a decline in phytoplankton, pelagic, and benthic species diversity in the Bohai Sea (Liu et al. 2011; Gao, Zhou, and Chen 2014). The mean marine trophic index (TRIX) declined by ≈ 0.2 per decade from the 1960s to 2000s, a rate that was higher than the global average for the same period (Pauly et al. 1998; Zhang, Tang, and Jin 2007).

We estimated the integrated ecological risk of the six different anthropogenic stressors on nine types of marine and coastal ecosystems of the Bohai Sea. We used the following equations to calculate integrated risks:

$$\text{Risk (Pollution)}_k = \sum_{j=1}^{n}\left\{\left(E_j \times \omega_{j,k}\right)\left[1+\sum_{i=1}^{m}\left(C_i \times \alpha_{i,j}\right)\right]\right\} \tag{1}$$

$$\text{Risk (Climate)}_k = \sum_{i=1}^{m}\left\{\left(S_i \times \mu_{i,k}\right)\left[1+\sum_{j=1}^{n}\left(P_j \times \beta_{j,i}\right)\right]\right\} \tag{2}$$

In these equations, Risk(Pollution)_k is pollution risk as impacted by climate change to ecosystem k; Risk (Climate)_k is climate-change risk as impacted by pollution to ecosystem k; E_j is the expected pollution risk of pollutant stressor j; C_i is the change rate of climate-change stressor i; S_i is the risk of climate-change stressor i; P_j is the over-standard rate of pollution stressor j; $\omega_{j,k}$ is the vulnerability weight for the pollutant stressor j on ecosystem k; $\mu_{i,k}$ is the vulnerability weight for the climate-change stressor i on ecosystem k; $\alpha_{i,j}$ is the impact weight of climate-change stressor i to pollution stressor j; $\beta_{j,i}$ is the impact weight of pollution stressor j to climate-change stressor i; m = 3 climate-change stressors, n = 3 pollution stressors, k = 9 ecosystems.

Data collection

All the data on pollutant concentrations and climate-change impacts were collected from field surveys, peer-reviewed journal papers, datasets, yearbooks, and IPCC reports, and cover all parts of the Bohai Sea (Liaodong Bay, Bohai Bay, Laizhou Bay and central area). In the case of multiple data in the same sampling point of the same year, the geometric mean was used.

Pollution risk assessment

Nitrogen and phosphorus, PHs and heavy metals were used as the indicators of environmental pollution risks. For nitrogen and phosphorus, the ecological risks include the possibility of eutrophication in aquatic systems. The ecological risks were assessed by using TRIX (Vollenweider et al. 1998). Risks from PHs and heavy metals were calculated with regional pollution probabilistic ecological risk assessment (RMPERA) based on toxicity data of indigenous plankton species (Solomon, Giesy, and Jones 2000). Only chronic toxicity data EC50 (concentration for 50% of maximal effect) and endpoints that could be clearly related to changes in population structure (such as growth, reproduction, and survival) were chosen. To build the risk cumulative distribution function, the species sensitivity distribution (SSD) function and the complementary function of exposure concentration distribution were integrated together. To unify the risk medium of nine ecosystems, we based all the pollution exposures on sea-water concentrations. Compared to sediment, sea water is affected by climate change more directly. Exposure concentration distributions and SSDs are integrated in the joint probability curves (JPC) to determine the risk of each pollutant in different periods.

Climate-change risk

SST, atmospheric CO_2 concentration and UV-B radiation intensity were used as the indicators of ocean warming, ocean acidification, and UV-B level. The risks for all these stressors were calculated by their impacts on ocean phytoplankton. SST risk was assessed by the effects of temperature on plankton biomass based on quantitative experiments. CO_2 risk was assessed by the effect of CO_2 concentration on plankton survival rate among multiple endpoints. UV-B risk was assessed by the SSD of UV-B effects on plankton EC50 based on quantitative experiments.

Vulnerability weights

The method for assessing the relative impact of stressors was based on expert judgments (Halpern et al. 2007) obtained through face-to-face interview. Ecosystem-specific differences in impacts of 6 climate-change and pollution stressors were estimated by peer-expert scoring. We received responses from 25 experts in 14 universities and institutes, representing a mix of academic, semi-governmental, and think-tank scientists with diversified backgrounds including marine science, climate-change study, ecology, and environment science. Experts were asked in interviews to assess the scale, frequency, functional impact, resistance, and recovery time of a threat to an ecosystem. Assuming equal weighting of the five vulnerability measures, we took the grand mean of their weighted averages to get a single rank that indicates how a given threat would affect a particular ecosystem. All score data were rescaled between 0 and 1.

Impact weights

An analytical hierarchical process (AHP) matrix was applied to get the impact weights between pollution stressors and climate-change stressors. Five experts were invited to give their scores for each pair of pollution and climate-change stressors. We took the mean of their score averages to get a single impact weight. The impact weights remain unchanged over time for different scenarios.

Results

We collected data on pollution and climate-change indices of the Bohai Sea from 1980 ~ 2014, covering a 35 years' period from the beginning of China's recent reform. Ecological risk was calculated for each stressor individually initially and then integrated for multiple stressors (Figure 3). PHs had the largest risk ratio of the six stressors, indicating nearly 50% plankton species in the study area are affected by PHs pollution with the assessment endpoint of EC50.

Nine different ecosystems were examined in this study area from the coastal to the deep marine (Figure 4). The risk of each stressor was calculated with an ecosystem vulnerability weight. Both pollution and climate-change stressors enhance each other in terms of ecological risk by different levels. The pollution risks for the 9 ecosystems were in the range of 39.7% (Sea-grass bed) ~ 56.4% (Beach), and enhanced to 43.2% ~ 61.8% by adding climate-change impacts. Climate-change risks were between 4.5% (Benthos) and 9.7% (Beach), which were increased to 6.5% ~ 10.4% under additional impacts of pollution.

Scenario analysis

For the past 35 years in the Bohai Sea region, the pollution risk has been decreasing, while the rate of climate change has been higher than the global average. We assumed that the pollution level in 2100 would remain at the level of 2014, and four different scenarios of climate-change risks for 2100 were projected (Figure 5): Scenario 1 was the changing trend over the past 35 years globally extrapolated to 2100; Scenario 2 was the changing trend over the past 35 years in Bohai Sea extrapolated to 2100; Scenario 3 was model projected Representative Concentration Pathway (RCP) 2.6, and Scenario 4 was RCP8.5 (IPCC 2014).

RCPs in the latest IPCC reports cover a wide range of climate model simulations to project their consequences, describing different pathways of greenhouse gas emissions and atmospheric concentrations, air pollutant emissions and land use in the twenty-first century. The RCP2.6 simulation assumes a stringent mitigation scenario, while RCP8.5 is a scenario with very high greenhouse gas emissions.

Compared to 2014, risks from pollution in 2100 will increase in three of the four scenarios (Figure 6). The only exception is RCP2.6, under which greenhouse gas emissions are strictly controlled, and

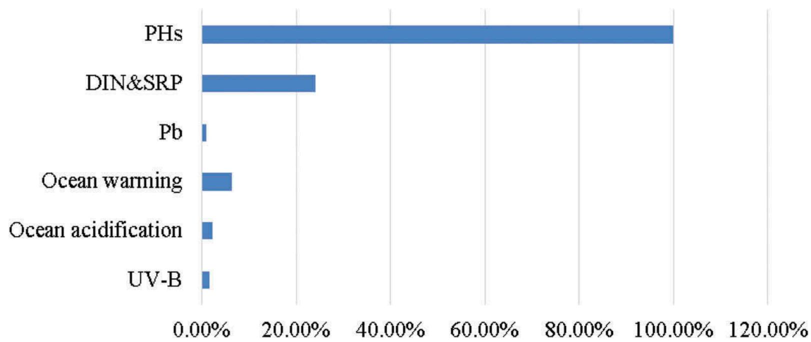

Figure 3. Ecological risks of pollution and climate-change stressors in Bohai Sea (1980–2014).

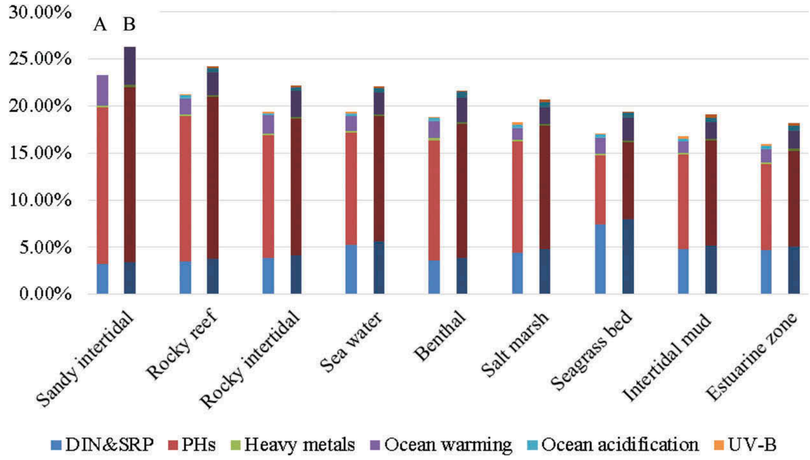

Figure 4. Integrated ecological risks of nine types of ecosystems in Bohai Sea (1980–2014). Bar A represents sum risk of multiple stressors adding directly; Bar B represents sum risk considering the interaction between pollution and climate change.

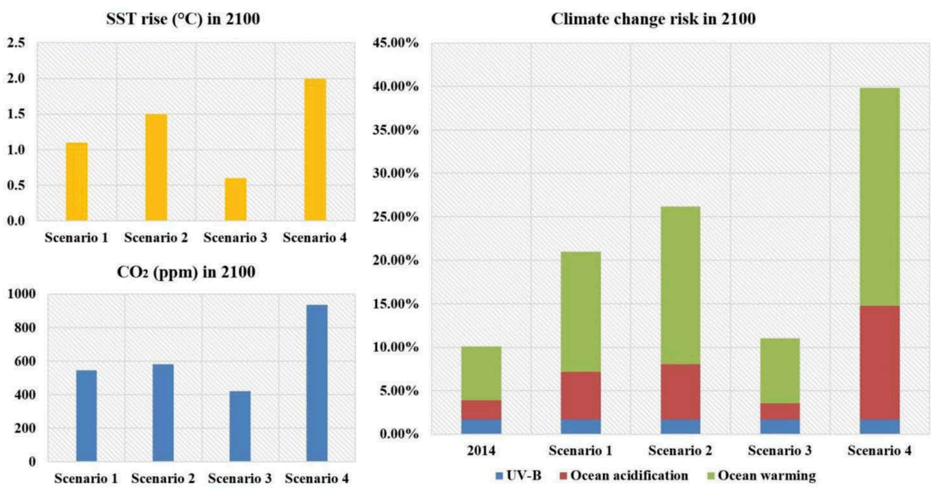

Figure 5. Climate-change risks in 2100 under four different scenarios.

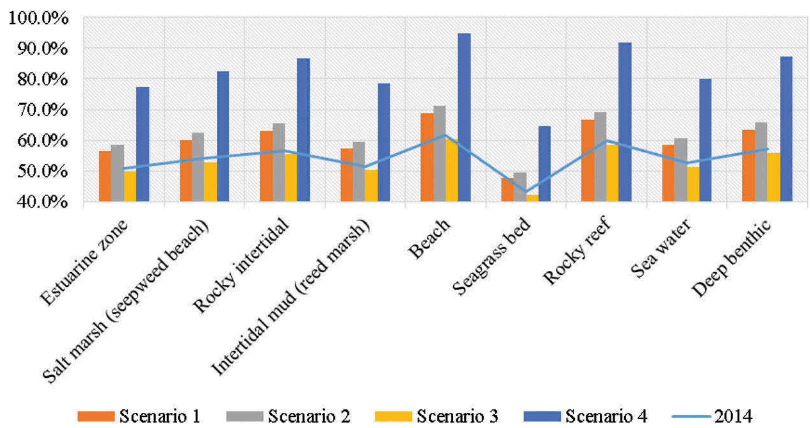

Figure 6. Combined pollution predicted impacts in 2100 as influenced by climate change under four scenarios in comparison to those in 2014.

pollution risks will decrease slightly compared with those in 2014. The ecosystems with lower pollution risk in 2014 will have higher shift rate in 2100 under the four scenarios, and low risks from pollution could be magnified to a higher level with interaction of climate change.

Discussion

Despite the diversity of these ecosystems and their many different organisms, the highest risks were typically associated with PHs. DIN and SRP were the outstanding risk stressors for sea-grass beds, linked to their high sensitivity to nutrients. The overall pollution risk for the seagrass bed is at a relatively low level, which may result from its richer biodiversity and greater resilience compared with other ecosystems (Figure 6). Higher sensitivity to pollution tended to be associated with ecosystems located in the terrestrial-aquatic transverse zone, including beaches, rocky reefs and the rocky intertidal zone, highlighting that these ecosystems are relatively fragile and vulnerable to anthropogenic pollution disturbances.

Climate-change risks have been accelerating, and pollution and climate change augment each other to bring about enhanced ecological risks to marine/coastal ecosystems.

In the scenario analysis, despite sea-level rise, the greatest climate-change threat in the future was predicted to be ocean warming followed by ocean acidification. UV-B was assumed to be constant in the four scenarios as it had a very small change during 1980 to 2014, and there is confidence that the ozone layer will continue to recover. We assumed that the impact weights between pollution and climate change were constant in all 4 scenarios. However, there is a possibility that impact weights may vary in different scenarios especially in the extreme conditions. We will consider this in future studies.

Although pollution risk has lessened over the last 5 years, many pollutants, such as metals, persist in the environment. The addition of climate change amplifies traditional stressors in these ecosystems. Disturbances from climate change and pollution could be combined to cause further deterioration in our ecosystems. The potential ecological shifts present major challenges for managers and policy makers. Clearly, reducing greenhouse gas emissions should remain a priority worldwide for managing the ecological risks in the next decades, not only because of temperature, acidification and UVB effects, but also its enhancing pollution risks. However, the risk analysis for the Bohai Bay area indicates the most important local activity should be the further reduction of PHs contamination. This PHs pollution on its own is a major stress and the potential for further ecosystem deterioration in combination with climate-change pressures will increase the risk. Our approach can easily be applied to regional scale risk planning and management of coastal ecosystems under the combined pressure of environmental pollution and climate change.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Author contributions

YL conceived the idea and study design. RW and YL drafted the paper, contributing equally as the first author. RW, YS, CS, and JY collected and analyzed data. All authors contributed to the analysis and interpretation, and commented on the draft paper. A. Johnson, A. Jenkins, RF, DC, HT, JM, and AE revised the paper.

Significance statement

Pollution and climate change are among the most significant environmental impacts on ecosystems resulting from current anthropogenic activities. Pressures from either climate change or pollution on ecosystems are often reported individually, yet we know little about the ecological risks under the combination of these pressures. In this study, we explore the effects of the interaction between environmental pollution and climate change, and their impacts on ecosystem health. Strengthened environmental management in China has decreased pollution risks in recent years. By contrast, climate-change risks have been accelerating, and pollution and climate change augment each other to bring about enhanced ecological risks to marine/coastal ecosystems. Recognition of this interaction is critical to formulating effective policies for integrated ecological risk management.

References

Backhaus, T., J. Snape, and J. Lazorchak. 2012. “The Impact of Chemical Pollution on Biodiversity and Ecosystem Services: The Need for an Improved Understanding.” *Integrated Environmental Assessment and Management* 8: 575–576. doi:10.1002/ieam.1353.

Behrenfeld, M.J., O’Malley, R.T., Boss, E.S., Westberry, T. K., Graff, J.R., Halsey, K.H., Milligan, A.J., Siegel, D. A., Brown, M.B. 2016. “Revaluating Ocean Warming Impacts on Global Phytoplankton”. *Nature Climate Change* 6: 323–330. doi:10.1038/nclimate2838.

Brown, A.R., Owena, S.F., Peters, J., Zhang, Y., Soffker, M., Paull, G.C., Hosken, D.J., Wahab, M.A., Tyler, C.R. 2015. “Climate Change and Pollution Speed Declines in Zebrafish Populations.” *PNAS* 106: 19211–19218.

Cramer, W. 2006. “Air Pollution and Climate Change Both Reduce Indian Rice Harvests.” *PNAS* 103: 19609–19610. doi:10.1073/pnas.0610075103.

Doney, S.C., Ruckelshaus, M., Duffy, J. E., Barry, J. P., Chan, F., English, C. A., Galindo, H. M. *et al.* 2012. “Climate Change Impacts on Marine Ecosystems”. *Annual Review of Materials Science* 4: 11–37. doi:10.1146/annurev-marine-041911-111611.

Doney, S. C., V. J. Fabry, R. A. Feely, and J. A. Kleypas. 2009. “Ocean Acidification: The Other CO_2 Problem.” *Annual Review of Materials Science* 1: 169–192. doi:10.1146/annurev.marine.010908.163834.

Gao, X., F. Zhou, and C. T. Chen. 2014. “Pollution Status of the Bohai Sea: An Overview of the Environmental Quality Assessment Related Trace Metals.” *Environment International* 62: 12–30. doi:10.1016/j.envint.2013.09.019.

Grimm, N.B., Chapin, F.S., Bierwagen, B., Gonzalez, P., Groffman, P.M., Luo, Y., Melton, F. *et al.* 2013. “The Impacts of Climate Change on Ecosystem Structure and Function”. *Frontiers in Ecology and the Environment* 11: 474–482. doi:10.1890/120282.

Halpern, B. S., K. A. Selkoe, F. Micheli, and C. V. Kappel. 2007. “Evaluating and Ranking the Vulnerability of Global Marine Ecosystems to Anthropogenic Threats.” *Conservation Biology* 21: 1301–1315. doi:10.1111/cbi.2007.21.issue-5.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D’Agrosa, C., Bruno, J.F. *et al.* 2008. “A Global Map of Human Impact on Marine Ecosystems”. *Science* 319: 948–952. doi:10.1126/science.1149345.

Hegglin, M. I., D. W. Fahey, M. McFarland, S. A. Montzka, and E. R. Nash. 2015. *Twenty Questions and Answers about the Ozone Layer: 2014 Update, Scientific Assessment of Ozone Depletion: 2014*, 84. Geneva, Switzerland: World Meteorological Organization.

Hoegh-Guldberg, O., and J. F. Bruno. 2010. “The Impact of Climate Change on the World’s Marine Ecosystems.” *Science* 328: 1523–1528. doi:10.1126/science.1189930.

IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva, Switzerland: IPCC.

IPCC. 2007. *Climate Change 2007: Synthesis Report*. Geneva: IPCC Secretariat.

Jin, P., T. Wang, and N. Liu. 2015. “Ocean Acidification Increases the Accumulation of Toxic Phenolic Compounds across Trophic Levels.” *Nature Communication* 6: 8714. doi:10.1038/ncomms9714.

Jing, X., J. Nathan, N. J. Sanders, and Y. Shi. 2015. “The Links between Ecosystem Multifunctionality and Above- and Belowground Biodiversity are Mediated by Climate.” *Nature Communication* 6: 8159. doi:10.1038/ncomms9159.

Karl, T. R., and K. E. Trenberth. 2003. “Modern Global Climate Change.” *Science* 302: 1719–1723. doi:10.1126/science.1090228.

Kong, P., Luo, W., Lu, Y., Wang, T., Jiao, W., Hu, W., Naile, J. E., Khim, J. S., Giesy, J. P. 2015. “Distribution and Bioaccumulation of Lead in the Coastal Watersheds of the Northern Bohai and Yellow Seas in China”. *Environmental Geochemistry and Health* 37: 491–506. doi:10.1007/s10653-014-9664-x.

Li, Y., Y. Zhao, S. Peng, Q. Zhou, and L. Ma. 2010. “Temporal and Spatial Trends of Total Petroleum Hydrocarbons in the Seawater of Bohai Bay, China from 1996 to 2005.” *Marine Pollution Bulletin* 60: 238–243. doi:10.1016/j.marpolbul.2009.09.020.

Liu, S., Lou, S., Kuang, C., Huang W., Chen, W., Zhang, J., Zhang, G. 2011. “Water Quality Assessment by Pollution-Index Method in the Coastal Waters of Hebei Province in Western Bohai Sea, China”. *Marine Pollution Bulletin* 62: 2220–2229. doi:10.1016/j.marpolbul.2011.06.021.

Luo, W., Wang, T., Jiao, W., Hu, W., Naile, J.E., Khim, J.S., Giesy, J. P., Lu Y. 2012. “Mercury in Coastal Watersheds along the Chinese Northern Bohai and Yellow Seas”. *Journal of Hazardous Materials* 215–216: 199–207. doi:10.1016/j.jhazmat.2012.02.052.

Matyssek, R., M. Schaub, and G. Wieser. 2010. “Air Pollution and Climate Change Effects on Forest Ecosystems: New Evidence.” *European Journal of Forest Research* 129: 417–419. doi:10.1007/s10342-010-0367-2.

Melissa, M-G 2014. “Pollution: A Global Threat.” *Environment International* 68: 162–170. doi:10.1016/j.envint.2014.03.023.

NBS (National Bureau of Statistics), PRC. 2015. *China Statistical Yearbook 2014*. Beijing: China Statistics Press, Beijing (in Chinese).

Oppenheimer, M. 1989. “Climate Change and Environmental Pollution Physical and Biological Interactions.” *Climatic Change* 15: 255–270. doi:10.1007/BF00138854.

Pauly, D., V. Christensen, J. Dalsgaard, R. Froese, and J. F. Torres. 1998. “Fishing down Marine Food Webs.” *Science* 279: 860–863.

Peng, S. 2015. “The Nutrient, Total Petroleum Hydrocarbon and Heavy Metal Contents in the Seawater of Bohai Bay, China: Temporal–Spatial Variations, Sources, Pollution Statuses, and Ecological Risks.” *Marine Pollution Bulletin* 95: 445–451. doi:10.1016/j.marpolbul.2015.03.032.

Peng, S., M. Dai, Y. Hu, Z. Bai, and R. Zhou. 2009. “Long-Term (1996–2006) Variation of Nitrogen and Phosphorus and Their Spatial Distributions in Tianjin Coastal Seawater.” *Bulletin of Environmental Contamination and Toxicology* 83: 416–421. doi:10.1007/s00128-009-9680-1.

Post, E., Forchhammer, M.C., Bret-Harte, M.S., Callaghan, T.V., Christensen, T.R., Elberling, B., Fox, A.D., *et al.* 2009. “Ecological Dynamics across the Arctic Associated with Recent Climate Change”. *Science* 325: 1355–1358. doi:10.1126/science.1173113.

Richardson, A. J., and D. S. Schoeman. 2004. “Climate Impact on Plankton Ecosystems in the Northeast Atlantic.” *Science* 305: 1609–1612. doi:10.1126/science.1100958.

Scholze, M., W. Knorr, and N. W. Arnell. 2006. “A Climate-Change Risk Analysis for World Ecosystems.” *PNAS* 103: 13116–13120. doi:10.1073/pnas.0601816103.

Smith Jr., K. L., H. A. Ruhl, B. J. Bett, R. S. Lampitt, and R. S. Kaufmann. 2009. “Climate, Carbon Cycling, and Deep-Ocean Ecosystems.” *PNAS* 106: 19211–19288. doi:10.1073/pnas.0908322106.

Solomon, K., J. Giesy, and P. Jones. 2000. “Probabilistic Risk Assessment of Agrochemicals in the Environment.” *Crop Protection* 19: 649–655. doi:10.1016/S0261-2194(00)00086-7.

SOA (State Oceanic Administration), PRC. 2015. *China Marine Statistical Yearbook 2014*. Beijing: China Ocean Press, Beijing. (in Chinese).

Taylor, G.T., Muller-Karger, F.E., Thunell, R.C., Scranton, M.I., Astor, Y., Varela, R., Ghinagliae, L.T. et al. 2012. “Ecosystem Responses in the Southern Caribbean Sea to

Global Climate Change". *PNAS* 109: 19315–19320. doi:10.1073/pnas.1207514109.

Taylor, R., R. L. Fletcher, and J. A. Raven. 2001. "Preliminary Studies on the Growth of Selected 'Green Tide' Algae in Laboratory Culture: Effects of Irradiance, Temperature, Salinity and Nutrients on Growth Rate." *Botanica Marina* 44: 327–336. doi:10.1515/BOT.2001.042.

van Dijk, J., B. Robroek, I. Kardel, and M. Wassen. 2012. "Combined Effects of Nitrogen Enrichment, Sulphur Pollution and Climate Change on Fen Meadow Vegetation N-P Stoichiometry and Biomass." *Biogeochemistry* 111: 139–150. doi:10.1007/s10533-011-9694-8.

Vollenweider, R. A., F. Giovanardi, G. Montanari, and A. Rinaldi. 1998. "Characterization of the Trophic Conditions of Marine Coastal Waters with Special Reference to the NW Adriatic Sea: Proposal for a Trophic Scale, Turbidity and Generalized Water Quality Index." *Environmetrics* 9: 329–357. doi:10.1002/(ISSN)1099-095X.

Xu, L., Wang, T., Ni, K., Liu, S., Wang, P., Xie, S., Meng, J., Zheng, X., Lu, Y. 2013. "Metals Contamination along the Watershed and Estuarine Areas of Southern Bohai Sea, China". *Marine Pollution Bulletin* 74: 453–463. doi:10.1016/j.marpolbul.2013.06.010.

Zeng, X., X. Chen, and J. Zhuang. 2015. "The Positive Relationship between Ocean Acidification and Pollution." *Marine Pollution Bulletin* 91: 14–21. doi:10.1016/j.marpolbul.2014.12.001.

Zhang, B., Q. Tang, and X. Jin. 2007. "Decadal-Scale Variations of Trophic Levels at High Trophic Levels in the Yellow Sea and the Bohai Sea Ecosystem." *Journal of Marine Systems* 67: 304–311. doi:10.1016/j.jmarsys.2006.04.015.