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Reversible effects of fertilizer use on population trends of waterbirds in Europe

A.P. Møller [a],*, K. Laursen [b]

[a] Laboratoire d'Ecologie, Systématique et Evolution, CNRS UMR 8079, Université Paris-Sud, Bâtiment 362, F-91405 Orsay Cedex, France
[b] Aarhus University, Institute of Bioscience, Grenåvej 14, DK-8410, Denmark

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ABSTRACT

Nutrients are often limiting primary productivity, and fertilizer use by agriculture increases primary and secondary productivity in marine environments. High levels of eutrophication due to fertilizer use can have negative effects on the distribution and the abundance of many organisms including waterbirds inhabiting freshwater and marine wetlands. Because nutrients, in particular phosphorus, can be stored in sediment, reversal of effects of eutrophication can take considerably longer time than the period during which effects of eutrophication build up. We quantified the effects of fertilizer use on 50 species of freshwater and coastal waterbirds monitored across Europe during 1982–2008 during the increase and the decrease phase of fertilizer use. More species were negatively affected by fertilizer use, and use of marine habitats during winter was the single-most important predictor of negative trends. The relative effect of fertilizer use on abundance of waterbird species was consistent during the increase and the decrease phase of fertilizer use. The effects of fertilizer use were statistically independent of the effects of climate change. Reversal of the effect of fertilizer use on population trends of waterbirds was almost three times as slow as the build-up of effects of nutrients on population size. These findings have management implications for the extent and the duration of fertilizer policies at local, national and international levels since these policies will partly determine the population trends and the population sizes of waterbirds.

1. Introduction

The industrial production of fertilizer had been assessed as one of the greatest discoveries by science due to its benefits for mankind (Conway and Toenniessen, 1999). Since production started in 1917 the use has spread across the world, and the amount of fertilizer used by farmers has increased by several orders of magnitude. The use of fertilizer has revolutionized the production of crops with great economic, social and demographic consequences. However, the use of fertilizer also had negative impacts on the terrestrial and aquatic environment. Effects of eutrophication on rivers, lakes and oceans are accumulating due to strong relationships between algal biomass and nutrient loading. Terrestrial ecosystems affected by nutrients dissolved in water or transported by air and precipitation cause a transition in the plant community from specialists of nutrient-poor to nutrient-rich soil. When nutrients exceed a certain level, eutrophic lakes are typically characterized by shifts towards dominance of phytoplankton (blue-green algae) (Vitousek et al., 1997; Jaworski et al., 1997).

Streams and rivers serve as rapid conduits for anthropogenic pollutants to estuaries and coastal marine waters, where nitrogen (N) has increased more than an order of magnitude and phosphorus (P) three-fold compared to pre-industrial inputs. Large amounts of N and P stimulate primary production (Pearson and Rosenberg, 1992; Karlson et al., 2002; Conley et al., 2007; Diaz and Rosenberg, 2008), secondary production (zooplankton and algae) and subsequently the size of fish populations (Nixon and Buckley, 2002). Such increases may have significant effects on abundance and distribution of piscivorous fish, birds and mammals. These positive effects of nutrients on abundance of fish may completely disappear or even become reversed by hypoxic, dead marine zones due to a diversion of energy from consumers to microbes (Baird, 2004). Such areas are devoid of most living organisms due to extensive hypoxia caused by high levels of nutrient release from farmland or cities, combustion of fossil fuels and anthropogenic fixed nitrogen in the atmosphere (e.g. Tyrrell, 1999; Rosenberg, 1985; Beman et al., 2005; Conley et al., 2007; Diaz and Rosenberg, 2008; Carstensen et al., 2014).

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* Corresponding author. Tel.: +33 1 69 15 56 88; fax: +33 1 69 15 56 96.
E-mail address: anders.moller@u-psud.fr (A.P. Møller).

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The total area of dead zones currently exceeds 200,000 km^2 worldwide with huge areas in Europe, North America and Asia being most severely affected with the area increasing exponentially (Rosenberg, 1985; Richardson and Heilmann, 1995; Beman et al., 2005; Conley et al., 2007; Diaz and Rosenberg, 2008; Carstensen et al., 2014). For example, the area affected by hypoxia in the Baltic Sea alone accounts for 60,000 km^2 with significant consequences for algae, plants, animals and humans alike (Carstensen et al., 2014). Although effects of dead zones mainly occur at large depths, there are documented effects on waterbirds that feed on benthos and bottom-dwelling and pelagic fish.

There are at least five categories of biological consequences of these processes leading to hypoxia and dead zones. First, primary productivity outside the winter period has more than doubled during a period of 50 years as a consequence of increased run-off of fertilizer to the marine environment (Pearson and Rosenberg, 1992; Richardson and Heilmann, 1995; Karlson et al., 2002; Conley et al., 2007; Diaz and Rosenberg, 2008). Second, the abundance of zooplankton has increased in response to higher abundance of phytoplankton (Nixon, 1992; Nixon and Buckley, 2002; Conley et al., 2007). Third, high levels of nitrogen and phosphorus in the marine environment have increased the abundance of benthos such as blue mussels *Mytilus edulis* (Nixon and Buckley, 2002; Laursen and Møller, 2014; Møller et al., 2015). Fourth, the abundance of fish has increased six- to eight-fold in Danish waters during part of the last century (Nixon, 1992; Nielsen and Richardson, 1996; Nixon and Buckley, 2002; Conley et al., 2007). This increase has been followed by recent reductions in distribution and abundance due to the formation of dead zones (Breitburg, 2002; Karlson et al., 2002; Conley et al., 2007; Diaz and Rosenberg, 2008) together with implementation of environmental control plans across Western countries to reduce pollution (Behrman et al., 1995). Fifth, the distribution and the abundance of top-predators such as birds have increased as a consequence of higher abundance of benthos, fish and other organisms, followed by a decrease as areas with hypoxia have expanded (Breitburg, 2002; Møller et al., 2007, 2015; Laursen and Møller, 2014).

These findings have implications for the recovery of ecosystems from extensive use of fertilizer in agriculture. The timescales required for recovery of ecosystems affected by hypoxia due to nutrient reduction plans are much longer than timescales of loss at the onset of hypoxia (Carstensen et al., 2006; Mee, 2006; Steckbauer et al., 2011). For example, Rosenberg et al. (2002) showed in a large-scale re-oxygenation experiment that the benthic community only partly recovered during a period of two years, while the effect of hypoxia on the community was almost instantaneous once levels of severe hypoxia had been reached.

The abundance of many waterbirds such as swans, geese, ducks, waders, gulls and terns closely follows the trend in fertilizer use (Møller et al., 2007, 2015; Laursen and Møller, 2014). In fact, while linear and quadratic effects of fertilizer use on population size of breeding waterbirds in Denmark accounted for 17% and 10% of the variance, linear effects of temperature and precipitation accounted for 22% and less than 1%, respectively (Møller et al., 2015). Likewise for wintering waterbirds the corresponding values were 12%, 3%, 12% and 1%, respectively (Møller et al., 2015). Hence the effects of climate and fertilizer were comparable. The temporal pattern of fertilizer use on farmland changed from a steady increase during most of the 20th century to a recent decline caused by changes in national and international farming policy (Møller et al., 2007). This raises the question whether the effects of fertilizer use on bacteria, algae, plants and animals are reversible and what is the time frame for the reversal process. Here we use extensive and long-term data on population trends of waterbirds inhabiting freshwater and marine wetlands to test for reversal of fertilizer effects. Specifically, we tested (1) whether the effects of fertilizer use on population trends of waterbirds were similar during the increase phase and the decrease phase of fertilizer use. In addition, we assessed (2) the effect of fertilizer use on waterbird populations by quantifying the magnitude of the effect during the decrease phase relative to the increase phase of fertilizer use. The logic behind this analysis is that populations of waterbirds during the increase and the decrease phase of fertilizer use are the same in most respects hence making it unlikely that other factors may account for similarity in slopes. Many factors other than fertilizer use may affect population size of waterbirds including climate change, changes in land-use and changes in nutrient input from sewage (Burton et al., 2002; Austin and Rehfisch, 2005; Maclean et al., 2008; Lehikoinen et al., 2014; Møller et al., 2015). Here we also tested for effects of climate change by including information on annual temperature anomalies during the study period. Furthermore, we included year as a continuous variable in the statistical analyses to account for any temporal trend in unknown confounding variables. Finally, we tested to which extent a number of potentially confounding variables would have affecting the conclusions about population trends and increase or decrease phase of fertilizer use. These variables were migration status, marine habitat during breeding, marine habitat during the non-breeding season, whether the species feed on land or in water, diet category such as fish, invertebrates or plants, hunting status, temporal autocorrelation in population size and similarity in phenotype among species due to common phylogenetic descent.

2. Materials and methods

2.1. Fertilizer use

Information on the relative amount of fertilizer use in Denmark was extracted from Duus and Zinglersen (2000), Hjorth and Josefson (2010), who reported annual combined amounts of natural and artificial fertilizers arbitrarily assigning a value of 100 to fertilizer use in 1950. Møller et al. (2007) showed that the concentration of nitrogen and phosphorus in the marine environment increased linearly with fertilizer use as reported by Duus and Zinglersen (2000), Laursen and Møller (2014), Møller et al. (2015) documented that these effects extended across different marine environments in Denmark.

We scored annual values of total fertilizer use in Denmark as belonging to the increase phase, if fertilizer use increased from the year prior to the focal year, or the decrease phase, if it decreased from the year prior to the focal year. The justification for this approach was to achieve two classes of years for the same general area, where one category of years had increasing fertilizer use and another had decreasing fertilizer use. Some years had changes in fertilizer use by almost 20% compared to the previous year (Fig. 1), and such changes are known to have large impacts on change in timing of reproduction, fecundity, survival and even population size of a number of bird species (Møller et al., 2007, 2015; Laursen and Møller, 2014). Such rapid effects are mediated by abundance and quality of food through effects of bottom-up trophic cascades starting with nutrients, phytoplankton, zooplankton, benthos and fish (Møller et al., 2015), affecting the extent of dead marine zones (Møller et al., 2015).

We obtained information on fertilizer use in the European Union from Eurostat (2011). The temporal trends in fertilizer use (total artificial fertilizer, nitrogen, phosphorus, phosphate, natural fertilizer) in Denmark were strongly positively correlated with fertilizer use for each of these five components in the 15 original member states of the European Union ($r^2 > 0.80$; Møller and Laursen, unpublished results). Because information on fertilizer use only is available for Western European countries since the 1960s,