CONNECTING LAND-USE WITH WATER QUALITY: SOURCES, SINKS AND TIME-BOMBS

KENNETH IRVINE, IAN DONOHUE, ALICE WEMAERE, DAVID STYLES & WILLIAM HOBBS

Centre for the Environment, Trinity College, Dublin 2, Ireland

ABSTRACT

The use of nutrient export coefficients provides a convenient means to estimate diffuse export of nutrients from catchments to lakes. Within individual catchments it is common to calibrate measured nutrients in surface waters with coefficients of intensity of land use, but the estimation of nutrient loads from one catchment based on export coefficients from another, albeit similar one, can be problematic. In the Lough Carra catchment in the west of Ireland, use of seemingly reasonable export coefficients, led to the estimation of about three times the measured load of phosphorus to the lake. This discrepancy is likely caused by low drainage density, high chemical buffering capacity of podzolic soils of the catchment and low historical intensification of the catchment relative to many other Irish grasslands. Nevertheless, profiles of lake sediment indicate progressive eutrophication of the lake, with associated reductions in Fe:P ratios indicative of impact from diffuse P loads. Lough Carra is one of the few remaining calcareous lakes in Europe managed to protect populations of wild trout (*Salmo trutta*). There is a high risk that continuation of current landuse in the catchment of the lake is an ecological time-bomb that will effect undesirable and persistent changes.

Keywords: buffer capacity, export coefficients, lakes, phosphorus loading

INTRODUCTION

The estimation of diffuse nutrient loads from catchments is problematic because it usually requires intensive spatial and temporal sampling programmes. The application of nutrient export coefficient models (Johnes *et al*., 1996; Heathwaite *et al*., 2003) in order to estimate loads is an attractive tool for management if coefficients estimated for one catchment can be applied to others with similar land-use patterns, topography and climate. The transfer of coefficients among catchments can, however, be problematic for reliable estimation of nutrient loads. The application of phosphorus export coefficients used by Johnes *et al*. (1994; 1996) in a study of 29 Irish catchments (Irvine *et al*., 2000; 2001) showed good correlation of ranking nutrient concentrations in lakes, but with a predictive power relating modelled to annual mean measured total phosphorus (TP) concentrations of <40%. These studies also showed measurements of annual mean in-lake TP to be strongly correlated to mean cattle density in the catchment and provided evidence that transfer efficiency of phosphorus export decreased in the order peatlands>siliceous>calcareous catchments. Daly *et al.* (2002) found run-off of soluble phosphorus from poorly drained and high production grasslands to be comparatively greater than that from well-drained soils. The well-drained catchments in the work of Daly *et al*. (2002) were dominated by brown earths and podzolics.

A relatively high capacity of phosphorus to be held in well-drained, especially deep, soils, likely relates to the availability of phosphorus binding sites. These catchments are not necessarily less vulnerable to excess nutrient loading but lag times before impact on surface waters may simply be longer than other catchment and, associated, soil types.

This paper describes 1) the nutrient status of a shallow calcareous lake, Lough Carra, impacted by diffuse nutrient loads and 2) an assessment of the application of nutrient export coefficient models applied to the catchment of L. Carra and of the nearby, River Robe, which drains to a large west of Ireland lake, Lough Mask.

STUDY SITE

Lough Carra (grid reference: 53º 42' N, 9º 13' W, Figure 1) has an area of just over 16 km^2, a mean depth of about 1.75 m and a maximum depth of 20 m. It is the largest marl lake in Ireland, a Special Area of Conservation under the EU Habitats Directive (92/43/EEC), and is one of the few remaining wild brown trout calcareous lakes in Europe. It has a catchment area of 114 km^2, which drains into Lough Mask, and comprises predominantly calcareous bedrock overlain with mostly grey-brown podzolics and brown earths. Land-use is mainly grassland used for sheep grazing, with some areas farmed more intensively for cattle, pigs and silage. Nutrients have been monitored since the 1970s and a recent summary is given in King and Champ (2000). The River Robe drains 286 km^2 of, mainly, grassland east of Lough Mask (Figure 1). Catchment characteristics are similar to Lough Carra, but with overall a greater proportion of high intensity land-use. A number of relatively small (total estimated <12000 p.e.; mean effluent discharge <1 mg l^{-1}) wastewater treatment works discharge to the river.

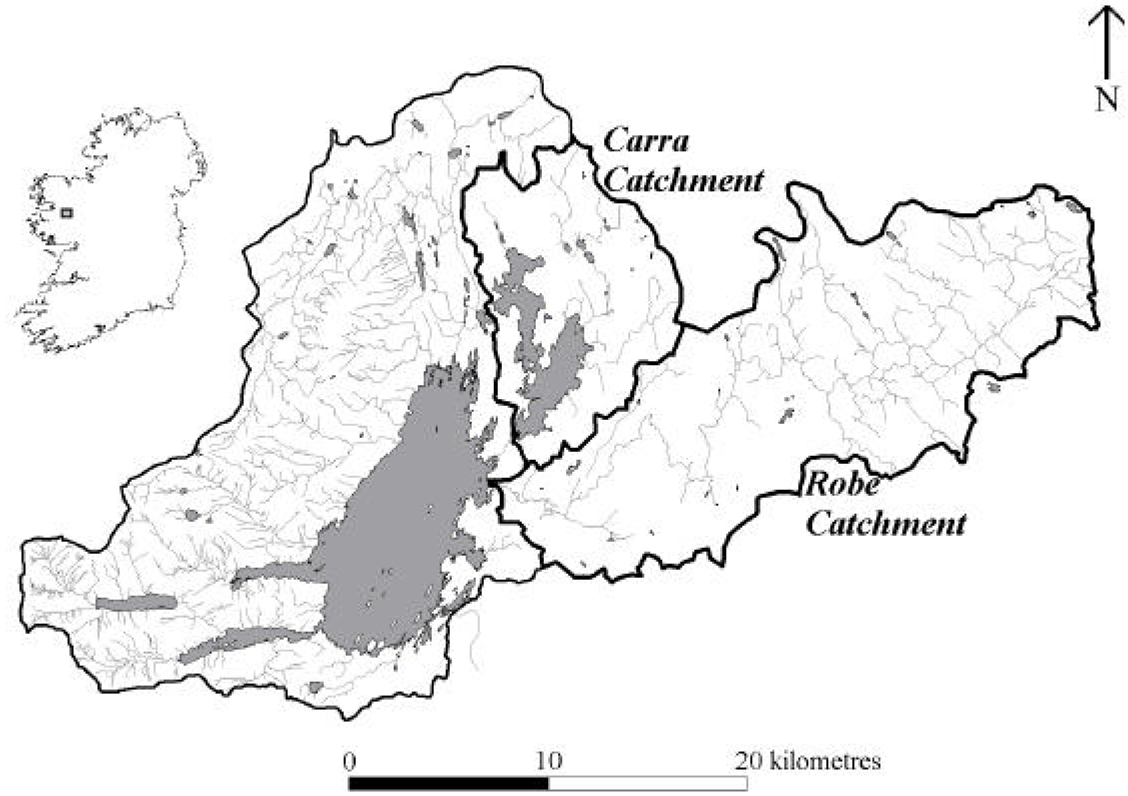

Figure 1. *Map of the Lough Mask catchment with the catchments of Lough Carra and the River Robe outlined.*

METHODS

Two export coefficient models were used to estimate the current total annual phosphorus (TP) loading of Lough Carra. The model of Jordan *et al.* (2000) is based entirely on CORINE land cover data and was calibrated for lakes in Northern Ireland, while that of Johnes *et al.* (1996) utilises data on agricultural stocking densities, human populations, and rainfall in addition to land coverage, and was calibrated for a number of different catchment types in Britain. Export coefficients applied to this study were those used by Johnes *et al.* (1996) from lowland calcareous grassland dominated catchments in the southeast of England. All land cover data used in the modelling of TP loads were obtained from CORINE landcover maps using ArcView® Version 3.2 as the GIS interface, while data on animal stocking densities and human population sizes were obtained from the national agricultural and human population censuses from 1991 and 1996, respectively. Predicted loads were used to calculate expected in-lake TP concentrations in Lough Carra and Lough Mask using a mass-balance "Vollenweider" empirical model developed by Foy (1992) for Irish lakes.

Monitoring of the River Robe, the three principal influent rivers to Lough Carra, which comprise approximately 95% of the total surface water inflow to the lake (Donohue, unpublished data), and the open waters of Lough Carra and Mask was done biweekly from July 2001 to July 2002 (Figure 1). Lake samples were collected with a 6 m tube of 2.5 cm internal diameter, which provided a vertically integrated water sample. Well mixed water samples from each sampling location were analysed, in triplicate, for total phosphorus, following Murphy and Riley (1962), using a Shimadzu UV-1601 spectrophotometer. Prior to analysis, samples were digested following Grasshoff *et al.* (1999). The discharge of the River Robe was calculated using daily flow records from an automatic water level recorder located at Foxhill Bridge (grid reference: 53º 39.5' N, 9º 09.3' W). As none of the influent rivers of Lough Carra are gauged, monthly hydraulic loads of each of the sampled rivers were estimated using rainfall measurements taken from the climatic station at Claremorris (grid reference: 52º 48.7' N, 8º 58.3' W), and proportioning out the total loading using flow data taken on a number of occasions.

In order to investigate historical load of phosphorus to Lough Carra, a single sediment core was taken from the deepest points in each of the three Lough Carra basins on July 24 and 25, 2002, using a 5 cm diameter modified Livingston core sampler. Immediately after collection, cores were extracted and segmented into 1 cm sections for subsequent analyses. Samples were stored in individual zip lock polyethylene bags and refrigerated at $4^{o}C$ upon return to the laboratory. Dry weight of sediment was estimated following 24 hours drying at $105^{o}C$. Sediment was analysed for TP after microwave nitric acid digestion using a CEM MDS-2000 microwave, following Eisenreich *et al.* (1975). Concentrations of iron (Fe^{3+}) were determined following microwave nitric acid digestion in the CEM MDS-2000 by flame atomic absorption (Clesceri *et al.*, 1998), using a Perkin Elmer Atomic Absorption Spectrophotometer 3100, following addition of 0.4% lanthanum to control interferences. Quality control standards were used in all of the above analyses, and were always within acceptable ranges.

RESULTS

The application of the export coefficient models of Jordan *et al*. (2000) and Johnes *et al*. (1996) resulted in predicted annual TP loadings to Lough Carra of, respectively, 5526 and 5516 kg. Total annual measured load for the year from July 2001 to July 2002, was 1728 kg, almost one-third of that predicted using the export coefficient models. The two models predicted similar mean concentration of TP in-flowing streams of 79 µg l^{1}, whereas the actual mean inflow concentration recorded was 25 µg l^{-1}. Mean in-lake concentration (± 95% C.I., Figure 2) measured in the sampling period was 10.4 ± 1.3 $^{-1}$. The application of the model of Foy (1992) to calculate average in-lake TP concentrations from weighed mean measurements from inflowing streams to Lough Carra predicted a mean concentration of 15.8 µg l^{1}.

Total annual TP load to the River Robe estimated from the export coefficients was 16045 kg (after Jordan *et al*., 2000) and 20827 kg (after Johnes *et al*., 1996). The measured load was 20068 kg. Estimated in-lake TP of Lough Mask, following Foy (1992) and accounting for all riverine inputs around the lake, was 8.9 µg l^{1}. Measured annual TP ((± 95% C.I., Figure 3) was 12.8 ± 2.7 µg l^{-1}.

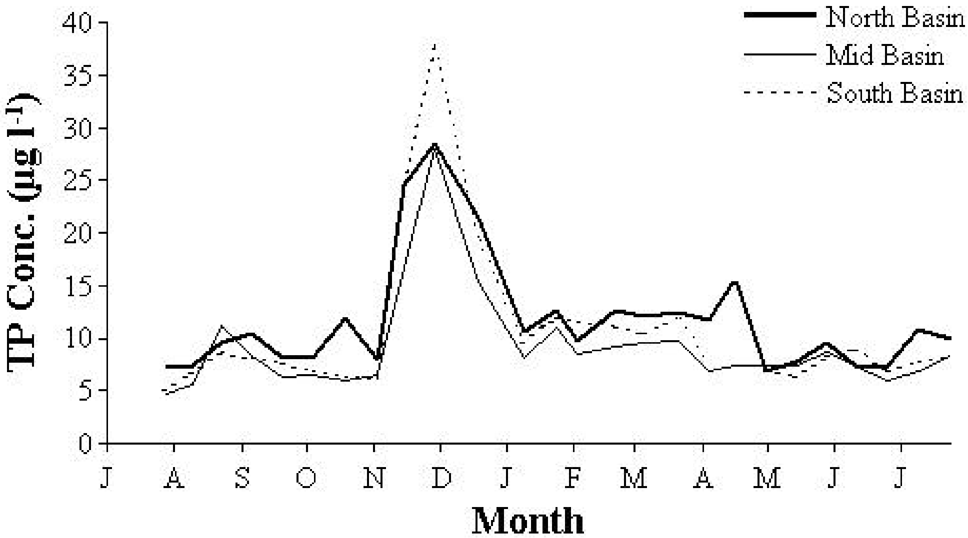

Figure 2. *Temporal variation in concentrations of total phosphorus in each of the three basins of Lough Carra, from biweekly samples taken in the period 26/7/2001 – 25/7/2002.*

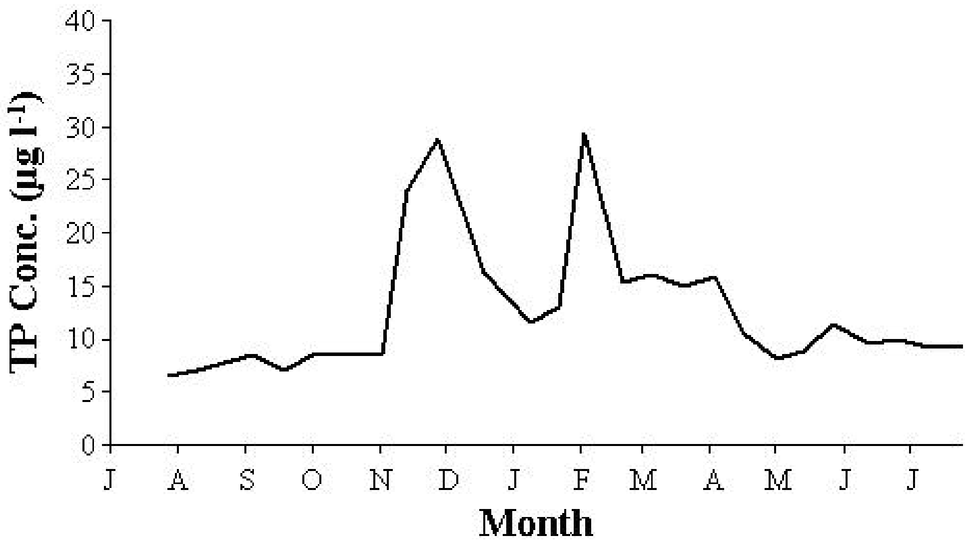

Figure 3. *Temporal variation in concentrations of total phosphorus in Lough Mask, from biweekly samples taken in the period 26/7/2001 – 25/7/2002.*

TP profiles in the sediment cores taken from each of the three Lough Carra basins showed increased sediment phosphorus concentrations in the upper 10 cm of each core (Figure 4(a)). In addition, although the molar ratio of Fe:P varied considerably in the core profiles, the ratio was considerably lower in the upper 10 cm of each core compared with deeper in the sediment (Figure 4(b)).

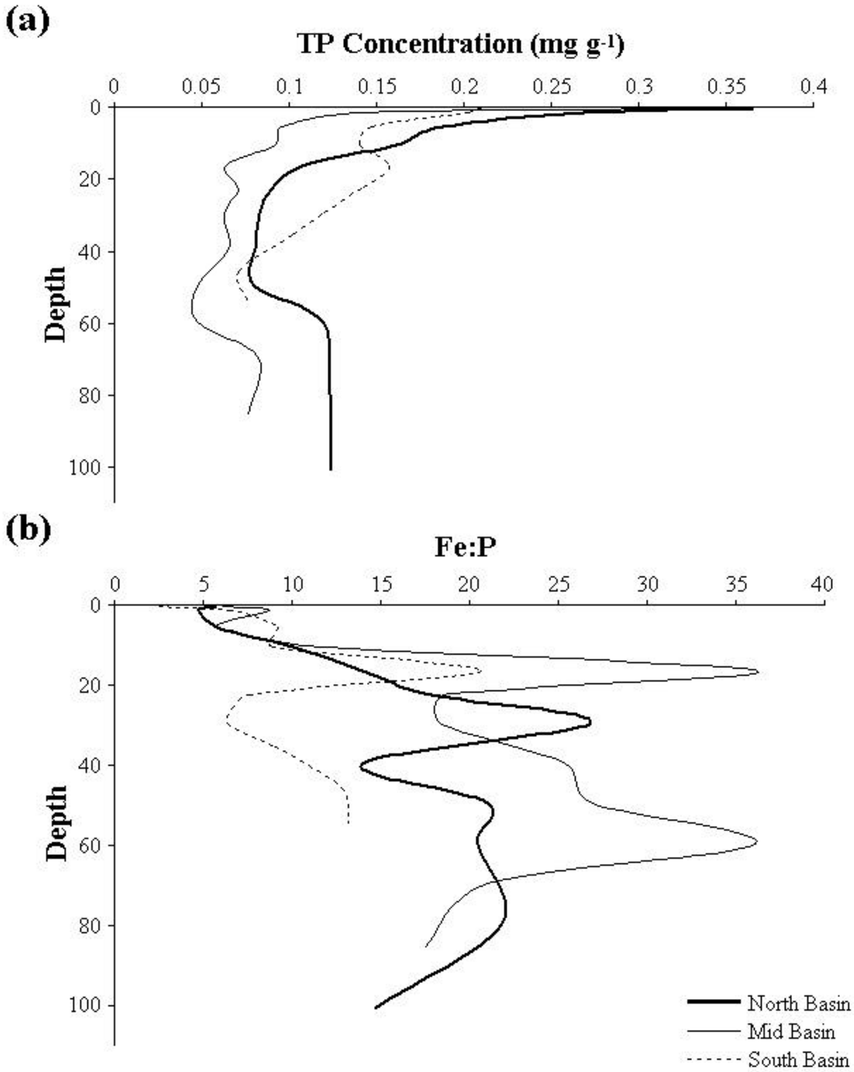

Figure 4. Profiles of (a) total phosphorus (mg g^{-1}) and (b) Fe:P (molar ratio) in the three Lough Carra cores.

DISCUSSION

Modelled phosphorus loads to Lough Carra were very similar for both the Jordan *et al.* (2000) and Johnes *et al.* (1996) models. A greater discrepancy was found for modelled loads to the River Robe, with the Johnes *et al.* (1996) model estimating about 30% more TP load than the Jordan *et al.* (2000) model. These differences could be due to variation among land-use categories and scaling effects (the Robe catchment is almost three times the area of the Carra catchment) but also suggest a multiplication effect of inappropriate weighting of export coefficients. The original calibration of an export coefficient model depends on tuning the model following original application through expert judgement or literature values of coefficients for each landuse category. This is an iterative approach described by Johnes *et al.* (1996) as calibration.

Irrespective of the fine-tuning required for the development of export coefficient models, our study suggests that there are some major differences between the catchment processes of the two catchments. For the River Robe catchment, the export coefficient models provided reasonable estimates of phosphorus load from the catchment to river, with the Johnes model within 5% of that derived from sampling. In contrast, the modelled loads in the Carra catchment were three times that of the measured concentrations. Two factors provide possible explanations for these differences. The first is that the drainage density (length of stream reaches per unit area) of the Carra catchment, at 0.7 km km^{-2}, is much lower than that of the Robe (2 km km^{-2}). This suggests that the connectivity between land and its drainage network is considerably lower in the Lough Carra catchment, resulting in lower phosphorus losses from land to water. The second is that landuse in the Carra catchment has been historically of lower intensity than that of the Robe. This is reflected in soil Morgan P values, which in the Lough Carra catchment are approximately half of those found in the Robe catchment (unpublished data). Both catchments are dominated by well-drained brown earths and grey-brown podzolic soils.

Whatever the mechanism for the observed differences between modelled export values of P may be, the results suggest that the characteristics of the Carra catchment mitigate strongly against the impact of diffuse phosphorus loads to the lakes. Nevertheless, evidence from the sediment cores indicate large increases in P load in the upper 10 cm of the sediment. This pattern is associated with a reduction of the Fe:P ratio and, hence, capacity of the lake to bind P (Jensen *et al.*, 1992; Lijklema, 1993). The implication of this is that the ecological impact of phosphorus loads to the lake has increased in recent years and, if loads continue at the present rate, will continue to do so. Future phosphorus loads may have proportionally greater impact than past ones. There is ample evidence that shallow lakes can switch over short time periods, and within narrow nutrient bands, from clear water lakes with rich beds of macrophytes to turbid ones, with altered or diminished macrophyte communities (Moss, 1983). Once such a switch occurs, homeostatic feedback mechanisms (Scheffer *et al*., 2001) can make subsequent restoration difficult, or impossible over short (decades) time periods. Potentially damaging sources of diffuse phosphorus from increasing agricultural intensification appear to have had a reduced ecological impact in Lough Carra, owing to hydrological, chemical and physical sinks that buffer nutrient transport to surface waters. The ecological and heritage importance of Lough Carra is high. There is a real risk that maintenance of current, or future, increases of diffuse nutrient loads constitute an ecological time-bomb that will effect ecological changes that are not only undesirable, but persistent.

ACKNOWLEDGEMENTS

The authors thank Manel Leira for help with collecting the cores and Norman Allott and Louise Scally with help in the lab. This research was funded by the 5th Framework EU Research grant, BUFFER (Contract No: EVK1-CT-1999-00019).

REFERENCES

Clesceri L. S., Greenberg A. E., Eaton A. D. and Franson M. A. H. (1998). *Standard methods for the examination of water and wastewater*. edn. 20, American Public Health Association, American Water Works Association and Water Environment Federation, U.S.A.

Daly K., Mills P., Coulter B. and McGarrigle M. (2002). Modeling phosphorus concentrations in Irish rivers using land use, soil type, and soil phosphorus data. *J. Environ. Qual*., **31**(2), 590-599.

Eisenreich S. J., Bannerman R. T. and Armstrong D. E. (1975). A simplified phosphorus technique. *Environ. Letters*, **9**, 43-53.

Foy R. H. (1992). A phosphorus loading model for Northern Irish lakes. *Water Res*., **26**(5), 633-638.

Grasshoff K., Kleming K. and Ehrhardt M. (1999). *Methods of seawater analysis*. edn. 3, Wiley, Chichester.

Heathwaite A. L., Fraser A. I., Johnes P. J., Hutchins M., Lord E. and Butterfield D. (2003). The Phosphorus Indicators Tool: a simple model of diffuse P loss from agricultural land to water. *Soil Use Mgt*., **19**(1), 1-11.

Irvine K., Allott N., Mills P. and Free G. (2000). The use of empirical relationships and nutrient export coefficients for predicting phosphorus concentrations in Irish lakes. *Verh. Internat. Verein. Limnol*., **27**, 1127-1131.

Irvine K., Allott N., de Eyto E., Free G., White J., Caroni R., Kennelly C., Keaney J., Lennon C., Kemp A., Barry E., Day S., Mills P., O'Ríain G., Quirke B., Twomey H. and Sweeney P. (2001). *Ecological assessment of Irish lakes. Final report*. Environmental Research R&D Report Series No. 12. Environmental Protection Agency, Ireland.

Jensen H. S., Kristensen P., Jeppesen E. and Skytthe A. (1992). Iron-phosphorus ratio in surface sediment as an indicator of phosphate release from aerobic sediments in shallow lakes. *Hydrobiologia*, **235**, 731-743.

Johnes P., Moss B. and Phillips G. (1994). *Lakes - classification & monitoring. A strategy for the classification of lakes*. R&D Project Record 286/6/A. National Rivers Authority, U.K.

Johnes P., Moss B. and Phillips G. (1996). The determination of total nitrogen and total phosphorus concentrations in freshwaters from land use, stock headage and population data: Testing of a model for use in conservation and water quality management. *Freshw. Biol*., **36**(2), 451-473.

Jordan C., McGuckin S. O. and Smith R. V. (2000). Increased predicted losses of phosphorus to surface waters from soils with high Olsen-P concentrations. *Soil Use Mgt*., **16**(1), 27-35.

King J. J. and Champ W. S. T. (2000). Baseline water quality investigations on Lough Carra, western Ireland, with reference to water chemistry, phytoplankton and aquatic plants. *Biol. Environ.-Proc. R. Irish Acad*., **100B**(1), 13-25.

Lijklema L. (1993). Considerations in modeling the sediment water exchange of phosphorus. *Hydrobiologia*, **253**(1-3), 219-231.

Moss B. (1983). The Norfolk Broadland: experiments in the restoration of a complex wetland. *Biological Reviews*, **58**, 521-561.

Murphy J. and Riley J. (1962). A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta*, **27**, 31.

Scheffer M., Carpenter S., Foley J. A., Folke C. and Walker B. (2001). Catastrophic shifts in ecosystems. *Nature*, **413**(6856), 591-596.