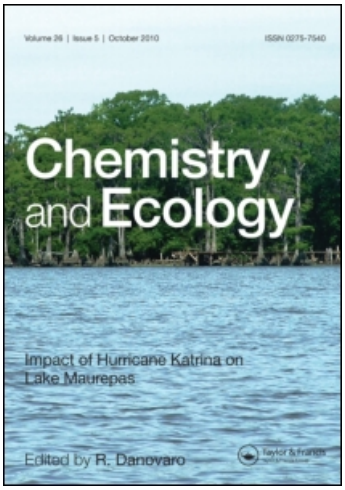

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Exploring the 'Birch effect' in reservoir sediments: influence of inundation history on aerobic nutrient release

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RESEARCH ARTICLE

Exploring the 'Birch effect' in reservoir sediments: influence of inundation history on aerobic nutrient release

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The release of nutrients on wetting ('the Birch effect') is well documented for terrestrial soils. The effect for aquatic sediments has received much less attention. An extreme drawdown event in a large reservoir during a period of drought presented an opportunity to test whether or not reflooding dried sediments would be a source of nutrients to the overlying water column. Wetting and drying history influences the release of ammonium, but not oxides of nitrogen, organic nitrogen, filterable reactive phosphorus or total phosphorus, from dried sediments following re-wetting. Dried reservoir sediments that have never, or have only rarely, been desiccated since the 1920s produced a pulse of ammonium on re-inundation. Conversely, dried sediments from parts of the reservoir that undergo frequent wetting and drying cycles do not release substantial amounts of ammonium on rewetting.

Keywords: sediment; drying; drought; nutrient release

1. Introduction

The release of inorganic nitrogen from dried soil on re-wetting, known as the 'Birch effect', is well documented in soil science literature [1–4]. Although not well understood, it has been suggested that the flush of inorganic nitrogen from re-wetting dried soils is caused by mineralisation of nitrogen by soil bacteria – the bacterial numbers being stimulated by the added moisture. For example, one study [1] showed that there was good agreement between aerobic respiration and inorganic nitrogen release.

While there have been numerous studies on the effects of drying and rewetting on soils, there has been little work done on the effects that drying and subsequent rewetting have on aquatic sediment processes [5] – notwithstanding the fact that both Mediterranean and tropical climate patterns predispose many aquatic systems to periods of drought and flood so that sediments are continuously undergoing wetting and drying cycles. Furthermore, predictions of climate change would suggest some regions will experience drier periods than they currently

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do [6]. Potentially, a release of nutrients to the overlying water could represent a pathway for the mobilisation of nutrients on refilling, which in turn could lead to eutrophication of the water body.

In one of the few studies on the effects of re-wetting desiccated sediments on N dynamics, Qui and McComb [7] clearly showed that there was a rapid flush of ammonia after re-flooding dried sediment-cores taken from a wetland. The ammonium concentration reached a peak after 4 days. As the level of ammonia began to decline, nitrate levels began to increase. The levels of nitrate continued to increase until all of the ammonia had been consumed. Unlike in soil systems, where the increase in N mineralisation is caused by an increase in microbial activity, it was suggested that the ammonia released came from a microbial biomass killed as a consequence of sediment desiccation. The ammonia was then converted to nitrate by microbially-mediated nitrification. In an earlier study [8] it was further suggested that a microbial biomass killed as a consequence of sediment drying may also lead to enhanced P release on sediment re-wetting.

Because the release of nutrients is related to microbial biomass, there has been some suggestion that frequent wetting and drying cycles would select for bacteria that are resistant to desiccation and therefore, the flush of nutrients on re-wetting would not be as noticeable [9].

The extreme drawdown of a large water storage reservoir during drought conditions in south-eastern Australia gave us the opportunity to test whether or not different drying regimes could lead to different sediment response on re-wetting and therefore, if rewetting could supply nutrients to the overlying water column. The drawdown exposed sediments that have only rarely been exposed (< 5 times) during the 80 years since the dam was commissioned. The response to re-flooding can be compared to sites that undergo frequent (approximately annual) wetting and drying cycles and those that are still inundated and therefore have probably never dried since the reservoir was commissioned.

2. Methods

Lake Hume is a large water storage on the Murray River near Albury, south eastern Australia (36°14′S, 147°15′E). The lake is fed by two major tributaries, the Murray River, which flows in from the northeast, and the Mitta Mitta River that flows in from the southeast. At full capacity (3.04×10^9 m^3) the lake has a surface area of 202.5 km^2 and a maximum depth of 41.4 m. At the time of sampling the lake was at about 3% of full capacity. The characteristics of the sediment in Lake Hume are described elsewhere and there are no significant differences in the mineralogy of the sediments from the Murray or Mitta Mitta River arms of the lake [10].

A microcosm experiment was undertaken to determine the extent of nutrient release from dry sediments upon inundation (under oxic conditions). Paired sites from both the Mitta Mitta and Murray River arms were chosen (Figure 1). Sediment samples (top – 3–5 cm) were taken from six sites on the dam – three sites on the Murray River arm and three sites from the Mitta Mitta River arm of the lake (Figure 1). One site from each arm was still inundated at the time of sampling and sediments from these sites have most likely never been exposed. One site from each arm was exposed at the time of sampling (i.e. were dry), but had a history of only very rarely being exposed to the atmosphere. One site from each arm of the lake was also dry at the time of sampling but these sites would undergo frequent (approximately annual) wetting and drying cycles.

Ten replicate sediment samples were randomly collected at each location over an area of about 1000–1500 m^2 and immediately placed into individual wide-mouthed pre-weighed 1-litre HDPE containers; each container held approximately 100 g of soil (on an air dried basis). On return to the laboratory all containers, with their sediment, were weighed. Five samples from each location were oven-dried at 30 °C for 2 weeks to simulate total desiccation; the change in weight following

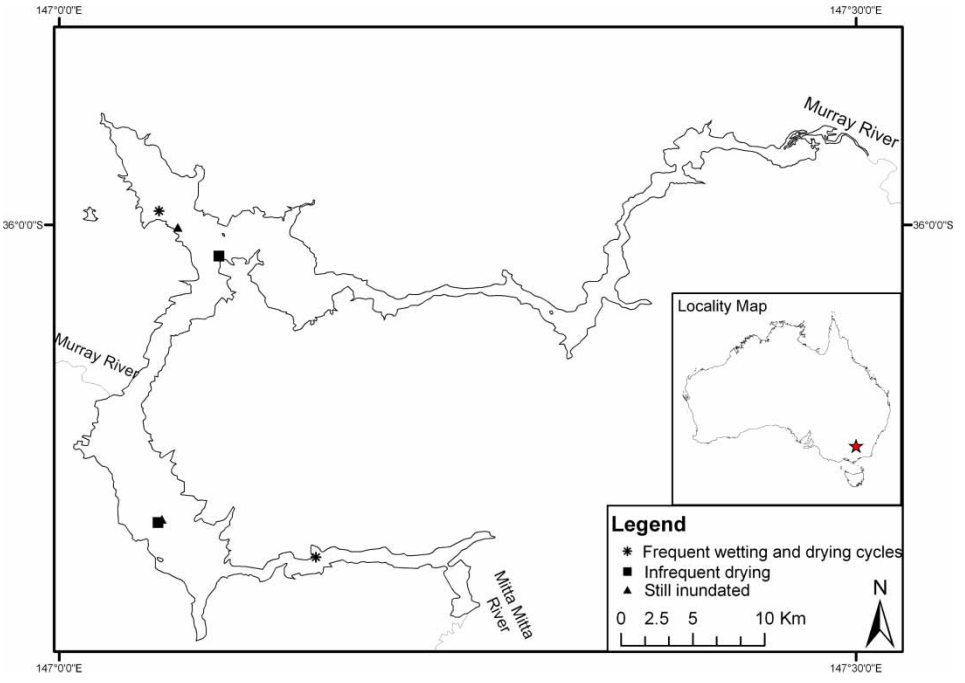

Figure 1. Map showing the six sampling sites. Outline shows the high water mark for the reservoir.

dessication was used to estimate the field soil moisture. The other five samples from each site (at field moisture content) were flooded with 600 ml of Milli-Q water adjusted to a conductivity of $300\,\mu S\,cm^{-1}$ with NaCl. The containers' mouths were sealed with foil, and kept in the dark at 20 °C in a constant temperature room for 21 days. Each container was regularly sampled for total nitrogen, total phosphorus, ammonia, oxides of nitrogen (NO_x – which is the sum of nitrate and nitrite) and filterable reactive phosphorus (frP). Five control containers (containing water but not soil) were also included in the incubation. Following drying, the samples placed in the oven were weighed then flooded and sampled in exactly the same manner.

All chemical analysis were performed by the MDFRC Analytical Chemistry Laboratory and using their quality assurance/quality control protocols. Total N and total P were determined on samples that had been first digested using the alkaline persulfate method of Hosomi and Sudo [11]. NH_4^+ was analysed using the phenate method, oxides of nitrogen ($NO_3^- + NO_2^-$) were analysed using the automated cadmium reduction method and PO_4^{3-} by the molybdenum blue method [12] simultaneously on a Lachat QuickChem 8000 auto analyser. Organic nitrogen was estimated from the difference between total N and ammonia + NO_x.

3. Results

Nutrient release was measured on soils that were initially at field moisture content and following oven-drying of the sediments at 30 °C for 2 weeks. (The average daily maximum temperature at Lake Hume over the austral Summer of 2006–07 was 32.5 °C [13]). The moisture content of the samples (mean ± standard error) from sites on the Murray River and Mitta Mitta arms of the lake that had remained inundated were 45 ± 2% respectively. The moisture content from the sites that rarely undergo drying (but were dry at the time of sampling) were 10 ± 2% and 3 ± 0.2% for the

Murray and Mitta Mitta sites respectively and, from the frequently dried sites the soil moisture content for the Murray and Mitta Mitta River sites were 1.6 ± 0.9 and $3.9 \pm 0.7\%$.

Sediments that were still under water at the time of sampling released almost no ammonium (Figure 2) or organic N (Figure 3) and only a small amount of nitrate (data not shown) following re-inundation without prior drying. They also only released a small amount of total phosphorus; however if sediments from these sites were dried in the oven prior to inundation (to simulate exposure and subsequent desiccation) they released substantial amounts of both nitrogen (mostly as ammonium – Figure 2) and total phosphorus (Figure 4).

Release of both organic N and total P following drying and re-inundation of sediments that had not previously been exposed was variable. Sediments from both sites released organic nitrogen and total P, but much more was released from the Mitta Mitta site than the Murray site. Further, there appeared to be a substantial lag phase from inundation to release of both organic N and total P at both sites. The release of organic N at both sites was linearly correlated with the release

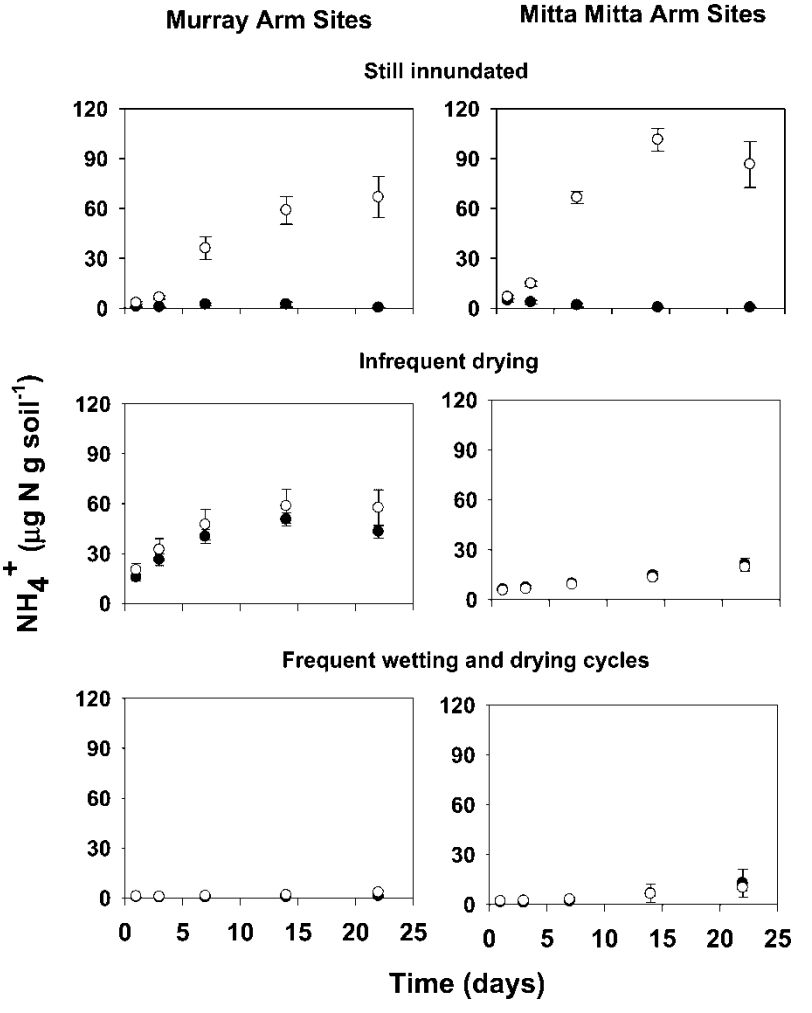

Figure 2. Release of ammonium following inundation of sediments from parts of the lake with different wetting and drying histories. Sediments at field moisture are shown as closed circles; oven-dried sediments are shown as open circles. Error bars represent the standard error ($n = 5$).

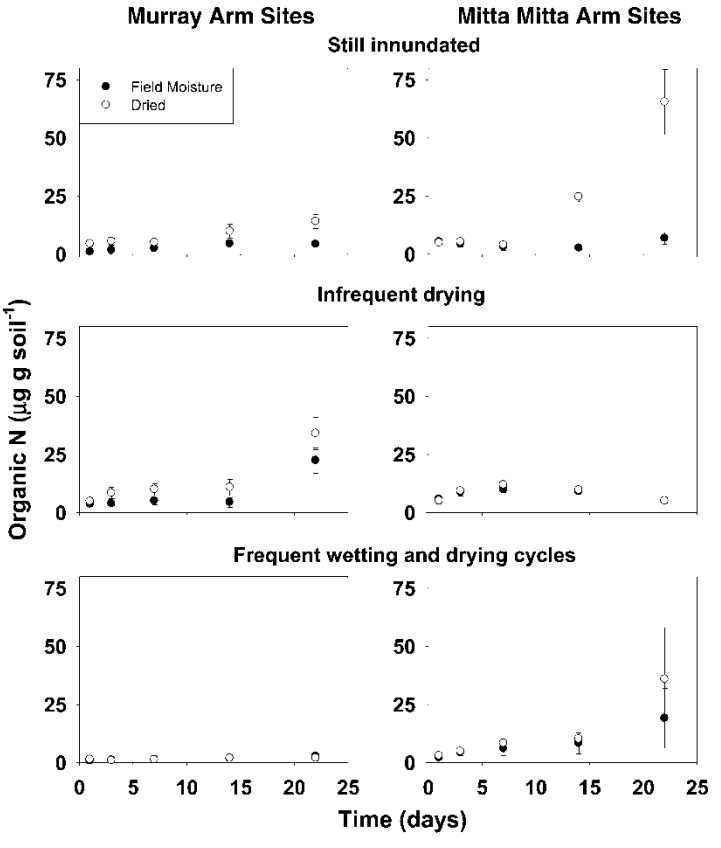

Figure 3. Release of organic nitrogen following inundation of sediments from parts of the lake with different wetting and drying histories. Sediments at field moisture are shown as closed circles; oven-dried sediments are shown as open circles. Error bars represent the standard error ($n = 5$).

of total P ($r^2 = 0.97$ if data from both sites was combined; $r^2 = 0.98$ and 0.99 if the sites were considered separately).

Sediments that had only occasionally been exposed over the life of the reservoir, but were exposed and dry during sampling, released nitrogen (again mostly as ammonia) on re-inundation; with substantially more nitrogen released from the sediment from the Murray River arm site than the site on the Mitta Mitta River. Additional oven drying of sediments from these sites did not stimulate any additional N release over that observed from sediments dried *in situ*. Measurable quantities of P were only released from the site on the Murray River arm, with oven drying not substantially increasing the amount of P released.

Very little ammonia was released following inundation of sediments from sites that have undergone frequent wetting and drying cycles; either at field capacity or following drying (Figure 2). Nitrate was released from the frequently inundated/exposed Mitta Mitta site on oven drying, but only from one replicate. Organic N was also released from the sediments at the Mitta Mitta site following oven drying, but again after a substantial lag phase. Furthermore, organic N release at this site was linearly co-related to the release of total P ($r^2 = 0.78$).

There was little release of filterable reactive P in any of the experimental treatments, with the highest recorded concentrations of 0.3 μgP g soil^{-1}, and most recorded concentrations near the detection limit of the assay.

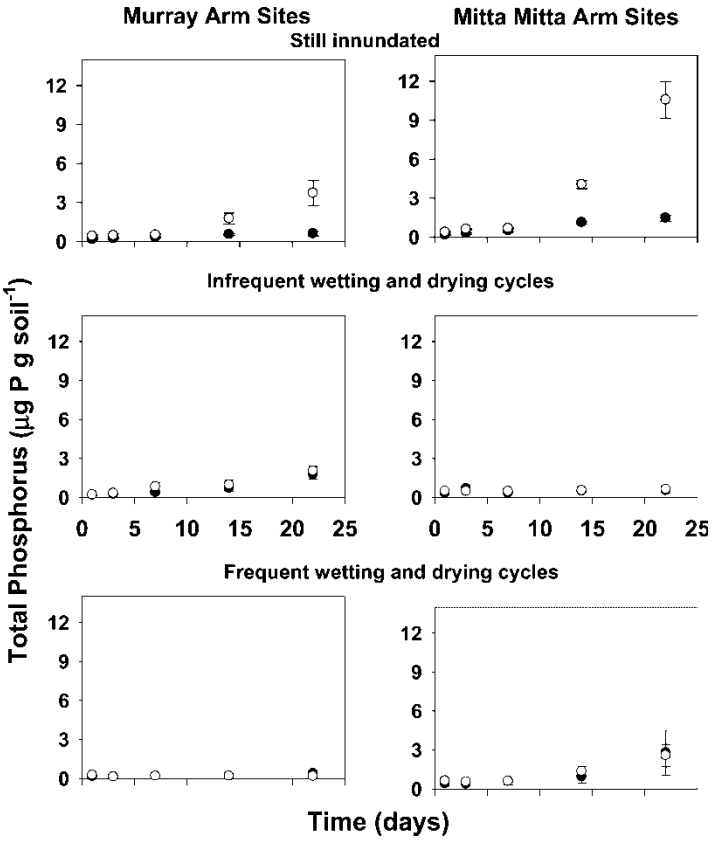

Figure 4. Release of total phosphorus following inundation of sediments from parts of the lake with different wetting and drying histories. Sediments at field moisture are shown as closed circles; oven-dried sediments are shown as open circles. Error bars represent the standard error ($n = 5$).

4. Discussion

The release of nutrients on wetting ('the Birch effect') is well documented for terrestrial soils (e.g. [1–4]). The effect for aquatic sediments has received much less attention. There is some evidence that something like the 'Birch effect' operates in sediments that have been dried and rewetted [7]. However, not all dried sediments release nutrients on re-wetting. In an earlier study it was shown that sediments from Lake Hume that see approximately annual wetting and drying cycles did not release nitrogen on rewetting [14]. Similarly, sediments from an old wetland that had undergone many wetting and drying cycles showed no evidence of a flush of phosphorus following re-wetting [9]. In both cases it was suggested that repeated wetting and drying cycles selected for microbial communities that could withstand desiccation.

In the current study we have shown that history of wetting and drying of a sediment influences its ability to release ammonium ions to the overlying water column following inundation; but its history does not appear to influence the release of nitrate, organic N frP or total P.

Sediments from sites that were still inundated during the period of extreme drawn-down event (to less than 3% of total reservoir capacity) probably had not been exposed since the reservoir was commissioned in the 1920s. If the sediments from these sites were re-inundated, under

oxic conditions, without drying, there was no release of ammonium. However, if the sediments were dried at a temperature similar to that which they would have been subjected to if exposed, then there was immediate release of significant amounts of ammonium ion. This observation is consistent with cell lysis. Bacterial cells in sediments that were still inundated would not undergo lysis. Similarly, re-suspension of the still wet sediments in water of a similar ionic strength to lake water also would also not induce lysis. Because the sediments were maintained under oxic conditions, anaerobic processes associated with N release from sediments such as dissimilatory nitrate reduction to ammonia or ammonification of organic N, could also not account for the initial pulse of nutrients.

Sediments that had only been exposed to desiccation infrequently during the life of the reservoir, but were dry at the time of sampling could also produce small pulses of ammonia on rewetting – with a much greater N release from sediments from the Murray arm rather than the Mitta Mitta arm. No additional ammonium was released from these sediments if they were subjected to additional drying in the laboratory, suggesting that *in situ* drying alone is sufficient to induce the ammonium pulse.

The observation that there was no ammonium release from sediments that came from areas that would undergo frequent wetting and drying cycles is consistent with the idea that frequent wetting and drying of sediments would select for sediment micro-organisms that were tolerant of changes in sediment moisture content [15].

Sediment drying history did not appear to directly influence the dynamics of NO_x, frP, organic N or total P from the sediments. There was an initial pulse of nitrate from the sediments for the still inundated site on the Mitta Mitta River, if the sediments were oven dried prior to inundation, but a similar effect was not seen at the corresponding Murray River arm site, nor to any great extent at the sites that have only undergone infrequent wetting and drying. Therefore, it is not possible to link the observed pulse of NO_x with drying-induced lysis. Similarly, while some sites showed elevated organic N and total P, the effect could not be ascribed to drying history. The substantial lag in the appearance of both organic N and total P at these sites, coupled with the high correlation between the two, at least suggests that these observed increases are as a result of bioavailable nutrients being released into the overlying water from the sediment and subsequently being incorporated into bacterial biomass. None of the treatments released appreciable amounts of frP.

This study has shown that dried sediments can be a source of ammonium to the overlying water column following re-inundation, but that the process is affected by the wetting and drying history of the sediments. The pulse of ammonium can, in turn, influence the ecology of the water body. Increasing nutrients can lead to an increase in overall algal biomass, so that if sediments are exposed and then re-inundated during the algal growth season it could lead to water quality issues. However, sediment desiccation and re-inundation could also be used to ameliorate water quality issues. For example, drying and re-wetting could be used to increase the ratio of inorganic N to inorganic P in the overlying water column, which in turn may influence the phytoplankton community structure; it has been suggested that low N:P ratios favour potentially toxic cyanobacteria. It is also possible that introducing numerous wetting and drying cycles could also be used to change sediment biogeochemical processes in water bodies suffering from a high internal loading of N.

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