



Nutrient release dynamics in relation to stages of *Lagarosiphon major* decay following treatment with diquat herbicide

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Abstract Herbicide treated weed beds release nutrients into the water column and have been implicated in providing ‘fuel’ for algal blooms. Here we assess the timing and magnitude of nutrient releases in relation to the visual signs of plant damage post-herbicide treatment. *Lagarosiphon major* shoots were exposed to one of eleven different diquat concentrations ranging from 0 to 1 mg l⁻¹ for 1, 10 or 100 min. Visual symptom of decay and total nitrogen (TN) and phosphorus (TP) concentration were monitored for 21 days after treatment. The largest rate and amount of TN and TP were released prior to and with shoot discolouration, suggesting a mechanism of diquat mediated cell lysis. Proportionally more P than N was released initially, and P releases became negative as the lagarosiphon decayed. N releases peaked with shoot discolouration, declining for the remainder of the assessment period, becoming negative when the shoot was deemed dead. The relationship between visual stage of decay and TN and TP release identified in this study could be used by lake managers to

help assess the role of herbicide treated weed beds in fuelling algal blooms but will need to be put into a lake specific framework.

Keywords Invasive aquatic weed · Herbicidal symptoms · Nitrogen · Phosphorus

Introduction

Macrophytes provide multiple ecological functions in aquatic ecosystems. Being primary producers, the biomass they produce directly supports aquatic food webs, whilst their physical structure is used by epiphytic algae, invertebrates and fish. Biogeochemically, they oxygenate the water column and sediment (Sand-Jensen et al., 1982; Woodward & Hofstra, 2022) whilst assimilating sediment nutrients (Carignan & Kalff, 1980). However, invasive aquatic plants can often out-compete native species, forming dense weed beds that cause significant negative impacts on freshwater ecosystems (Closs et al., 2004). Such invasions reduce biological diversity and reduce the abundance and distribution of native macrophytes in invaded systems (Closs et al., 2004). These beds also reduce the recreational amenity of a water body by impeding swimming, fishing, water sports and boat use. Given the undesirable impacts of invasive aquatic plants, their distribution and abundance is often controlled to support native biodiversity and/or amenity use. Methods to reduce the

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abundance of invasive weed beds include physical, biological and chemical means. Amongst these, herbicide is a cost-effective method for reducing weed beds particularly at large scale where they have saturated the habitat (Madsen, 2000; Hofstra et al., 2018; Muller et al., 2021). However, herbicide use will result in decaying macrophyte biomass which could have ecological consequences via increased nutrient availability and enhanced rates of oxygen consumption, but the potential scale of these impacts has not been documented.

Amongst the literature on invasive weed control there are authors that associate the release of nutrients from decaying plant matter with algal blooms (Landers, 1982; Sabol, 1987; James et al., 2002), whilst others show no increase in nutrient levels or subsequent algal blooms (Brooker & Edwards, 1973; Serdar, 1997). The timing of post weed control algal blooms varies, which makes identifying the cause of such blooms difficult. For example, in Lake Champlain, the decay of shredded water chestnut biomass resulted in an increase in chlorophyll concentrations of 31 g l^{-1} , 7 days after shredding (James et al., 2002). Similarly, Sabol (1987) noted that Chl a concentration doubled within 9 days of harvest, shredding and disposal of *Hydrilla verticillata* in Orange Lake. Whereas, in pond-based experiments which utilised four ponds with approximately equal biomass of *Elodea canadensis* Michx., algal blooms formed 5 months post diquat treatment (during the next summer) with the largest bloom in a pond that been experimentally fertilized four years earlier (Peverly & Johnson, 1979). Landers (1982) investigated the effect of biomass decay, from naturally senescing *Myriophyllum spicatum*, on nutrients and chlorophyll-a concentrations using in-lake mesocosms with and without macrophytes. They found algal blooms occurred in summer, in line with the peak nutrient input from decaying macrophyte biomass, and presumably warm summer water temperature. The occurrence of algal blooms post weed control is dependent on temperature, and the availability of nutrients and light to support algal growth. Therefore, background nutrient concentrations, hydraulic residence times, temperature and the availability of light all interact with the nutrient content of treated weed-beds, the rate of weed decay and nutrient release rates, to influence the potential occurrence of algal blooms following the treatment of invasive weed beds.

Nutrient releases from decaying macrophyte biomass has been observed using laboratory experiments (Nichols & Keeney, 1973; Wang et al., 2018; Xiong, 2019), pond scaled experiments (Peverly & Johnson, 1979) and in treated lakes (James, 1984) and has been found to be dependent on both macrophyte characteristics and environmental factors. Environmental factors include water temperature (Ogwada et al., 1984), dissolved oxygen concentrations (Nichols & Keeney, 1973) and, nitrogen, carbon & phosphorus contents of the sediment (Peverly & Johnson, 1979). Internal macrophyte characteristics may also influence releases, such as cells with higher C:N (carbon to nitrogen), C:P (carbon to phosphorus) ratios release less N and P into the water column than macrophytes or macrophyte components with lower C:N and C:P ratios (Chimney & Pietro, 2006; Wang et al., 2018).

The decay of macrophyte biomass is microbially mediated (Wang et al., 2018) with the release of water soluble nutrients playing a key role in the initial loss of biomass (Varga, 2003). This initial pulse often has a high phosphorus content. Phosphorus (P) concentrations have been observed to reach their maximum about 15 days after the start of decay and then decrease gradually over time (Chimney & Pietro, 2006; Carvalho et al., 2015). Peak nitrogen (N) concentrations have been observed to occur soon after peak P release (Li et al., 2014). Post peak releases, decaying biomass has been observed to be a sink for P (Wang et al., 2018). There is a need to identify simple metrics that could be used to predict nutrient release dynamics to better understand the potential for those nutrients to contribute to algal blooms following weed control. As a first step, we aim to establish the relationship between the visible symptoms of treated plant decay, with their rate of TN and TP release. The timing and magnitude of nutrient release and attenuation relative to visual symptoms could then be used in control works programmes to better understand causal relationships between herbicide efficacy, the presence of additional nutrients in the water column and the potential timing of any algal blooms.

Methods

Lagarosiphon major (lagarosiphon) was propagated from a culture at National Institute of Water and Atmospheres Ruakura Aquatic Research facility.

Plants were propagated in trays of garden soil covered in a thin layer of sand, in tanks with a water depth of 80 cm which were covered with 80% shade cloth. This common garden setting was used to maximise the number of lagarosiphon plants that were growing under the same conditions from which uniform shoots could be collected for each of the replicated laboratory trials that are reported on here. Lagarosiphon shoots were treated with diquat concentrations that ranged from 1 mg l^{-1} (efficacious treatment rate (Clayton & Matheson, 2010)) and decreased exponentially to 0.001 mg l^{-1} (Table 1) with exposure time of 1, 10 or 100 min for all concentrations. The treatments were undertaken in a series of 5 experiment runs. Each experimental run included three diquat treatment concentrations (doses) and in any given experimental run (other than the first) the lowest dose from the previous experiment was repeated (Table 1).

For each experimental run, 150 lagarosiphon shoots, 15 cm in length were harvested from the common garden. The treatment doses of diquat herbicide (see Table 1) were prepared in separate tubs, and 45 shoots were placed in each tub of herbicide (3 herbicide rates per experimental run). After the exposure periods had elapsed, 15 shoots were removed from each treatment tub, triple rinsed in tap water, and then three shoots were placed into a 1 l beaker filled with tap (municipal supply) water (1l). There were five replicates of each dose rate and exposure period combination. Untreated controls were replicated in five beakers each containing 3 untreated shoots. Each of the beakers was labelled with the diquat treatment concentration, the exposure time, and the replicate number. The beakers were placed on the bench in the constant temperature room (20°C), that was running a day:night cycle of 14h:10h with ca. $146 \mu\text{mol/m}^2/\text{s}$

PAR. Each beaker had a tube inserted into the water for continuous aeration from a compressor. Post-treatment, the shoots remained in the beakers for a period of 21 days (assessment period) during which time visual observations of herbicidal symptoms were made and 60 ml of water from the beakers was sampled for TN and TP analysis. Water lost from evaporation and sampling was replaced (and volumes recorded). Assessments occurred at 4 h after treatment (HAT) and 1, 4, 7, 10, 13, 16, 19, and 21 days after treatment (DAT).

The symptoms of decay were assessed using a scale from 0 to 5, as follows: 0—green and healthy, 1—discoloured or dull, 2—loss of turgor, 3—fragmentation, 4—collapsed, and 5—dead. Destructive harvest of all viable plant material was undertaken 21DAT. The harvested material was oven dried at 60°C and when constant, dry weights were recorded. In addition to the treated plants and the untreated control plants, a further 15 shoots were removed from the common garden culture to provide an estimate of initial biomass ($0.18 \pm 0.08 \text{ g}$) and N and P content of the lagarosiphon ($3.5 \pm 0.5 \text{ mg N}$ and $0.5 \pm 0.06 \text{ mg P}$ per 1 g plant dry weight). Samples for N and P content analysis were dried and ground. N content was analysed by Dumas combustion, and P by digestion (nitric and hydrochloric acid) followed by filtration and analysis on an IPC-OES.

The sampled water was analysed for total nitrogen and total phosphorus concentrations. All samples were digested with persulphate digest (APHA 4500P, APHA 4500N), TN was analysed using cadmium reduction (QuikChem 31-115-01-1-I) and TP using molybdenum blue (QuikChem Method:31-107-04-1-A), on a Flow Injection Analyzer. TN and TP concentrations were converted to masses by multiplying their concentration by the volume of water in the jar at the time of sampling.

Data analysis

All reported concentrations of TN and TP were converted into masses by multiplying the observed concentration by the volume of water that was in each beaker at the time of sampling. This mass was then normalised to the dry weight of the untreated shoots (controls) recorded at the end of each experiment. These nutrient concentrations were then corrected for the ongoing release of nutrients that occurred

Table 1 Diquat concentrations and exposure period used in each experimental run

Experiment run	Diquat treatment rate (ppm of active ingredient)	Exposure period (minutes)
1	1, 0.5, and 0.25	1, 10, and 100
2	0.25, 0.125 and 0.064	1, 10, and 100
3	0.064, 0.032 and 0.016	1, 10, and 100
4	0.016, 0.008 and 0.004	1, 10, and 100
5	0.004, 0.002 and 0.001	1, 10, and 100

in control beakers to isolate only the effect of the applied diquat. This correction can result in a negative concentration, indicating the decaying biomass was a sink not a source of TN or TP.

The resulting data has been analysed and presented in a number of ways. Firstly, as a simple time-series of TN and TP concentrations. Secondly, TN and TP release rates between each sampling points were calculated by dividing the difference in mass of TN and TP between sequential sampling points by the duration between the two sampling points. These release rates were then grouped by the stage of visual decay and mean TN and TP release rates calculated. This method means that each beaker was represented multiple times, at different levels of decay as the plant shoots move through each of the decay stages. Thirdly, the average time that it took to reach each stage of decay was calculated by grouping symptoms alone or by diquat dose and symptom, and calculating the average DAT for these groups. As “dead” was considered an endpoint, to calculate the time it took to “dead”, only the first observation of “dead” for each beaker was included. Multiple “dead” observation would have artificially inflated the time to “dead”. Fourthly, load of TN and TP released per gram of dry biomass between each sampling point was calculated for each jar in each experimental run. This was undertaken by multiplying the TN or TP hourly release rate by the time (in hours) between each sampling point. These loads were then grouped by symptom level to allow average loads (and associated error) per symptom level to be calculated.

Statistical analysis

PERMANOVAs were used throughout the analysis due of non-normal distribution of the data and unbalanced designs of many of the tests performed (Anderson, 2014). Three statistical designs were used. The first was a one-way PERMANOVA which investigated the effect of dose on either TN or TP concentration across all sampling points. The second was a repeated measures PERMANOVA, where time after treatment and dose were fixed variables, used to assess the effect of diquat dose on the concentration of TN and TP found during the assessment period. For this analysis, exposure time was not included as during field application to the opportunity to control exposure period is limited. Finally, PERMANOVAs

were also completed to determine differences in TN and TP release rates at the different decay stages both within each diquat dose (two-way), and across all doses (one-way). PERMANOVAs were completed in Primer7®.

Results

The effect of dose and exposure on decay rates

Neither the non-treated controls nor the shoots treated at the lowest dose of 0.001 mg l^{-1} and lowest exposure period, showed signs of decay during the 21-day assessment period. As doses increased from 0.001 mg l^{-1} , greater exposure periods hastened the rate of progress through the signs of decay up to a dose of 0.016 mg l^{-1} . For diquat doses higher than 0.016 mg l^{-1} exposure period did not affect the rate at which the shoots decayed. The shortest time to death was 10 ± 0.0 days, which occurred with all exposure periods for diquat doses greater than 0.016 mg l^{-1} . The longest time to death was 21 ± 0.0 days, which occurred with a dose of 0.001 mg l^{-1} and exposure period of 10 min. A table providing the time taken after treatment to reach each visible symptom for each dose and exposure combination is provided in the supplementary materials.

Temporal dynamics of nutrient release

One-way PERMANOVA revealed that diquat dose had a significant ($P < 0.001$) effect on the concentrations of TN found in the experimental beakers when all times after treatment were combined. Repeated measured PERMANOVA showed that when all diquat doses were combined (see Table 1 diquat doses), exposure period ($P < 0.001$) and time after treatment ($P < 0.001$) were both significant but no interaction was found. Across all doses (Fig. 1f), TN concentrations slowly increased until 13 DAT and then slowly decreased until the end of the assessment.

Across all observation points, a one-way PERMANOVA revealed that diquat dose significantly ($P < 0.001$) affected the concentration of TP found in the beakers during the assessment period. Repeated measures PERMANOVA showed that across all tested doses (see Table 1 for diquat concentrations), exposure period ($P < 0.001$) and time after treatment

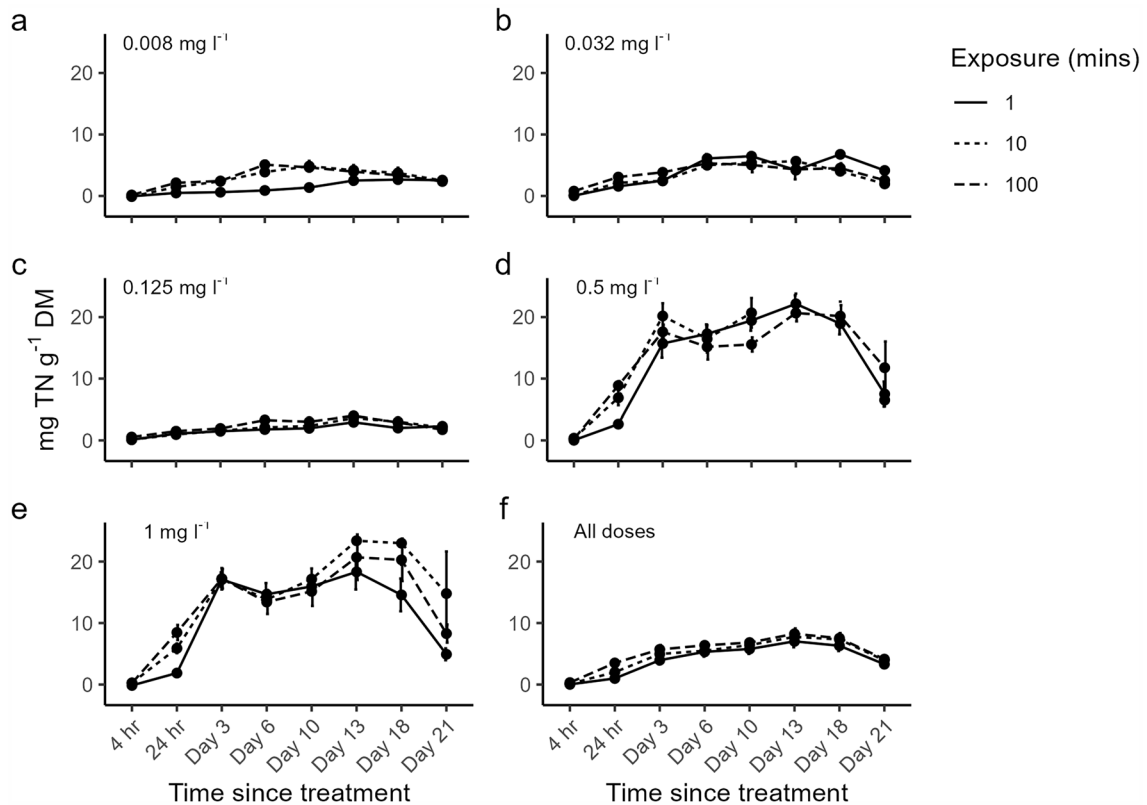


Fig. 1 The release of TN through time after treatment at different diquat concentrations (top left of each graph) for the three different exposure periods (top right). For the full list of diquat concentrations see methods

($P < 0.001$) were both significant and an interaction between exposure period and time after treatment was found ($P < 0.001$). Exposure period affected the magnitude of P released during the first 3 days after treatment. The longer the duration of exposure the greater the release of P from the treated biomass, within the first 3 DAT. After 3 days the differences in concentration related to exposure period decreased until 6 DAT, when the trend remained similar and largely constant for the duration of the experiment (Fig. 2f).

Nutrient release rates and loading at each stage of decay

Stage of decay had a significant effect on the rate of TN release when averaged across all diquat treatments and exposure periods ($P < 0.001$). The highest rate of TN release occurred when plants were discoloured, and this was significantly ($P < 0.05$) greater than at all other visible stages of decay. Healthy (0)

shoots had the next highest, which although significantly ($P < 0.05$) less than that of discoloured (1) shoots, was significantly ($P < 0.05$) higher than at all other stages of decay. Shoots that had lost turgor (2) and were fragmented (3) had similar rates of TN release as did collapsed (4) and dead shoots (5). Overall, releases tended to be higher in the early stages of decay (symptom levels 0–1) where average release rates were 7.5 ± 0.6 , $8.1 \pm 1.0 \mu\text{g TN g DM}^{-1} \text{ h}^{-1}$, respectively. During later stages of decay (symptom levels 2–5) average TN releases decreased to 3.7 ± 0.7 , 0.2 ± 0.8 , 0.4 ± 0.7 and $-1.35 \pm 0.4 \mu\text{g TN g DM}^{-1} \text{ h}^{-1}$, respectively (Fig. 3).

The level of decay also had a significant effect on the rate of TP release when averaged across all diquat doses and exposure periods ($P < 0.001$). The highest P release rates occurred when the lagarosiphon shoots still appeared to be “healthy” (0) which had significantly higher rates of release than for all other decay stages. Discoloured shoots (1) released P at a

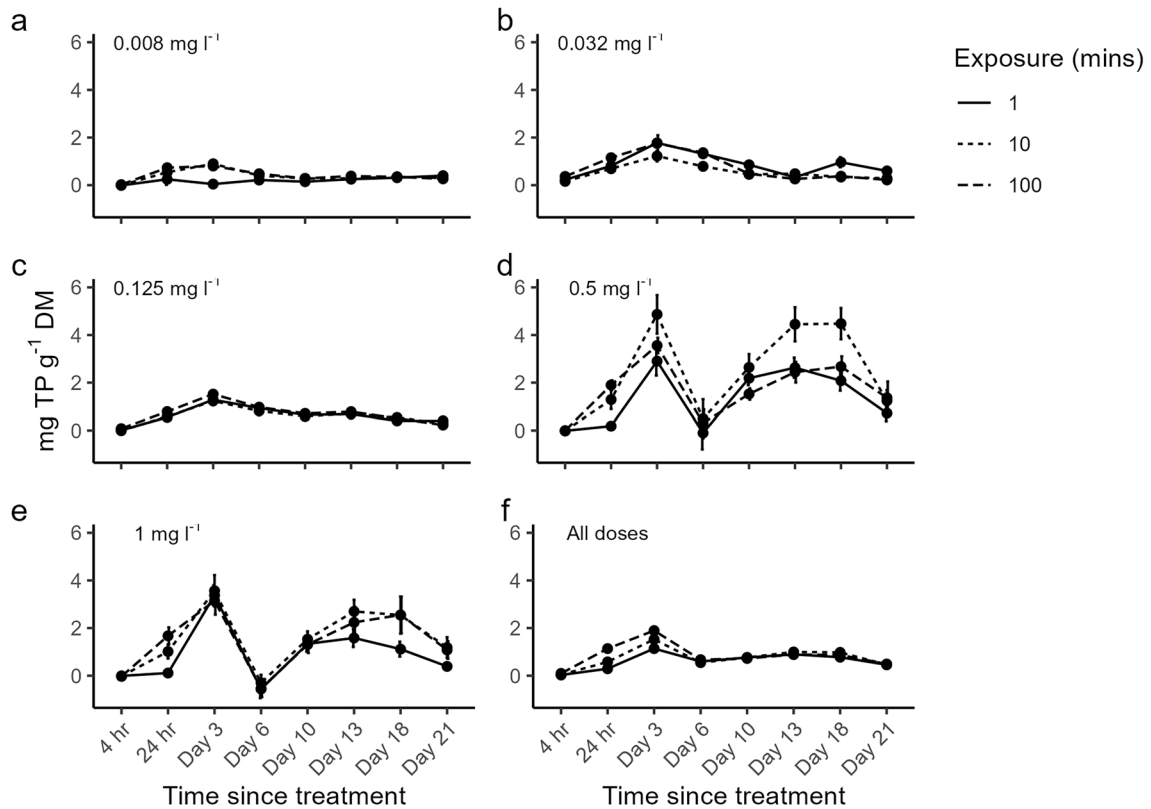
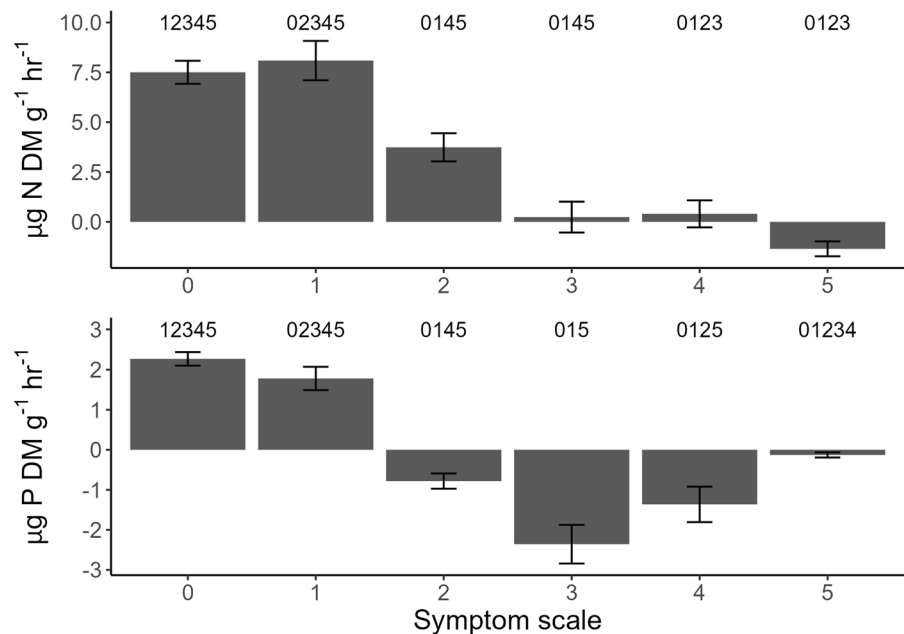


Fig. 2 The release of TP through time after treatment at different diquat concentrations and exposure periods. Diquat concentrations are on the top left of each graph, and exposure periods are on the top right of the figure

Fig. 3 Average TN and TP release rates (positive load is release and negative load is uptake) with error bars representing one standard error of each visible symptom of decay averaged across all diquat doses and exposure periods (see methods for details). The visible symptoms were: (0) healthy, (1) discolouration, (2) loss of turgor, (3) fragmentation, (4) collapse, and (5) dead. Numbers in the upper section of each graph denote which symptom levels significantly differed from each other



significantly lower rate than healthy (0) shoots, but was still significantly higher than all other levels of visible decay ($P < 0.05$). TP releases become negative at a visible symptom of “loss of turgor” (2) and were most negative when “fragmented” (3). TP releases increased again at the stages of “collapse” and “dead” (5). Average rates of TP release, across all diquat doses and exposure periods, were 2.3 ± 0.2 , 1.8 ± 0.3 , -0.8 ± 0.2 , -2.4 ± 0.5 , -1.4 ± 0.4 , 0.1 ± 0.1 $\mu\text{g TP g DM}^{-1} \text{ h}^{-1}$, respectively across all of the different levels (0 to 5) of visual decay (Fig. 3).

The load of TN ($P < 0.001$) released per gram of dry mass was significantly affected by the visual stage of decay, average loads ($\pm \text{SE}$) ranged from 412 ± 50 to -106 ± 28 $\mu\text{g of TN DM g}^{-1}$ (Fig. 4). TN loads highest during “discoloration”, and were significantly different from all other visual stages of decay ($P < 0.05$). The second largest load of TN released occurred before any visual symptoms of decay were evident (“healthy”), and were also significantly different from all other visual decay stages. The “loss of turgor” stage released the third largest load of TN and was significantly different from all other stages of visual decay. The final three stages of visual decay were statistically similar to each other, although the load released became negative during the death stage.

The load of TP ($P < 0.001$) released per gram of dry mass was significantly affected by the visual

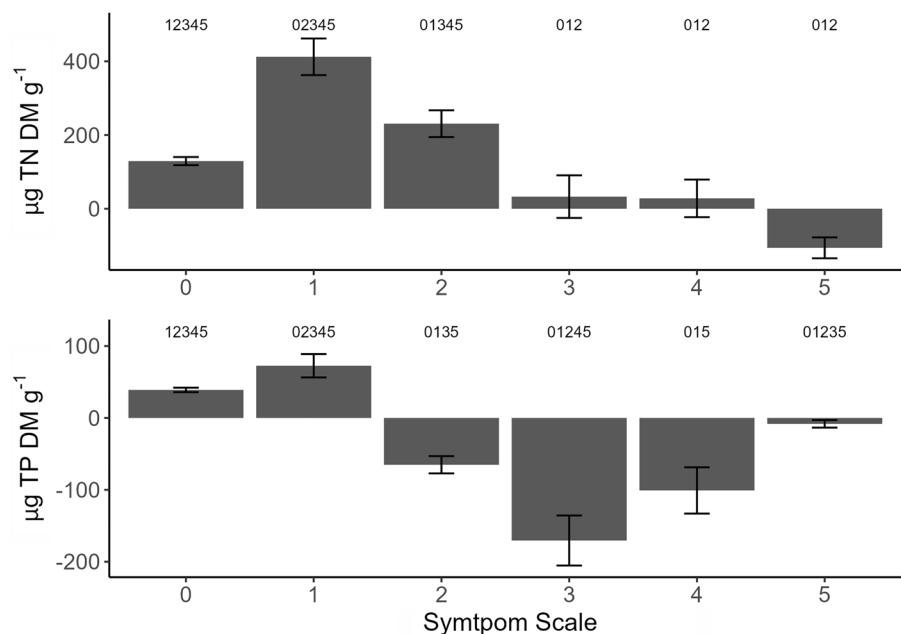
stage of decay, ranging from 73 ± 16 to -170 ± 35 $\mu\text{g of TN DM g}^{-1}$. Visual decay stages of healthy and discoloured had the highest load released, significantly greater than all other stages ($P < 0.01$). The next greatest load of TP released occurred whilst the plants had no visible symptom, which was also found to be significantly different all other stages of decay ($P < 0.01$). During all of the subsequent stages of visual decay, the biomass was a sink for TP. The greatest load of TP was up taken during fragmentation, which was significantly greater than all other stages apart from the collapsed stage ($P < 0.001$).

Discussion

Time to symptoms

A wide range of diquat doses were used to treat the lagarosiphon shoots in this experiment. This range was aimed at replicating the range of concentrations that are likely to occur during a field diquat application where dilution, dispersion and adsorption rapidly reduce the diquat concentration and exposure period that target weeds receive. As may be anticipated, the rate of progress through the visible symptoms of decay decreased with decreasing diquat dose. However, above a dose of 0.016 mg l^{-1} , diquat dose and

Fig. 4 Average load of TN and TP released or up taken at each visible symptom of decay. Error bars representing one standard error. Averages are across all diquat doses and exposure periods (see methods for details). The visible symptoms were: (0) healthy, (1) discoloration, (2) loss of turgor, (3) fragmentation, (4) collapse, and (5) dead. Numbers in the upper section of each graph denote which symptom levels significantly differed from each other



exposure period did not affect the rate of decay. This lack of an effect of exposure period may be caused by diquat adsorbed onto and absorbed into plant tissue (Davies & Seaman, 1968) lessening the effect of exposure period when diquat concentrations were high enough to saturate the lagarosiphon shoot. Additionally, plant decay, after a lethal diquat dose, is microbially mediated and its rate is likely dependent on the size and metabolic rate of the microbial community facilitating the breakdown of lagarosiphon biomass. Thus, the rate of decay of a treated plant is largely independent of the diquat dose and exposure period, so long as a lethal treatment was applied. However, below a dose rate of 0.016 mg l^{-1} , most shoots still died but took longer than 10 days to die, suggesting that although doses were lethal the shoots were healthy enough (initially) to slow the rate of microbially mediated decay.

Temporal dynamics of nutrient releases

Higher diquat doses caused larger releases of both TN and TP and this happened sooner after treatment, than from shoots treated with the lower diquat doses. Diquat is a photosynthesis inhibitory herbicide that works by intercepting an electron from the photosynthesis I pathway, resulting in the formation of reactive oxygen species which damage lipids, DNA, RNA, proteins as well as cell walls, resulting in cell lysis (Summers, 1979). The present study shows that the higher the diquat dose the larger TN and TP releases that likely result from a larger number of cells being lysed.

Our study and previous studies on nutrient dynamics from decaying aquatic macrophytes have found that peak TP releases occurred before peak TN releases, (Nichols & Keeney, 1973; Chimney & Pietro, 2006). Our experiments were conducted without sediments and with aeration, which may have enhanced the TP releases whilst reducing TN releases. Nichols & Keeney (1973) tested the effects of endothall treatment on *Myriophyllum exalbescens* with and without sediment and aeration. They suggested the breakdown of the *M. exalbescens* biomass was N limited as it appeared that any extra N supplied from the sediments was used to aid in the breakdown of *M. exalbescens*. In contrast, TN concentration during our assays do not appear to limit the breakdown of the lagarosiphon biomass as there were

only slight decreases in TN concentrations throughout the experimental period. Comparatively, the sharp declines in TP concentrations may indicate that the microbial population breaking down the lagarosiphon biomass became P limited between 3 and 6 days after treatment.

TP concentrations peaked early in our assay and sharply declining between 3 and 6 days after treatment. This pattern suggests a large initial release of soluble P from the lagarosiphon biomass which was then utilised by the microbial population breaking down that biomass. Nichols & Keeney (1973) identified that in their water only systems, P was released rapidly and over half was as dissolved reactive phosphorus and thus available for microbial utilisation. Such releases of readily available P help explain the rapid declines in TP concentrations observed around day 6 of our assessment period. Neither Nichols & Keeney (1973) nor Wang et al., (2018) observed a sharp decline in concentration similar to that which occurred during the present study despite having similar concentrations of P in the biomass of the macrophytes they investigated. It is unclear why the microbial population appear to have become P limited between days 3 and 6 in our study.

Nutrient release and symptom level

The highest rates and loads of TP release came from plants that still appeared “healthy” (0). This is likely due to the lysing of cells caused by diquat treatment and the release of any soluble nutrients contained within these cells (Varga, 2003), the resulting cell damage only becoming visibly apparent (as discolouration) hours to days after the lysing had begun. The slowing of the release of TP from treated shoots likely coincides with the period after the majority of the cells have been lysed from the diquat treatment and the releases have become influenced by the microbially mediated breakdown of the biomass. On average, the “discolouration” stage of decay lasted 28 h compared to 85 h for the “healthy” stage, with the release rate of TP declining compared to the “healthy” stage, but TN release rates were at their highest. The shorter duration of the “discolouration” stage resulted in the loads of TN and TP released decreased compared to the lengthy “healthy” stage. The disparity in the timing of the greatest release rates of N and P from decaying macrophyte biomass is commonly observed

(Nichols & Keeney, 1973; Wang et al., 2018) and is likely because a greater proportion of a cell's P stores are in dissolved form compared to N, allowing a comparatively faster release of P than N (Chimney & Pietro, 2006; Wang et al., 2018).

Post diquat treatment, the microbial utilisation of the lagarosiphon biomass will progress from more easily broken-down cells, which have lower C:N and C:P ratios, to more structural, lignin and cellulose rich cells, with higher C:N and C:P ratios (Chimney & Pietro, 2006; Wang et al., 2018). This pattern can be seen in both the signs of visual decay, as the shoots lose their structural integrity and in the decreases in the rate of TN and TP releases which eventually become negative. Average TP release rates decreased from an initial high at the “healthy” stage and become negative at the “loss of turgor” stage. This is likely to coincide with the onset of the breakdown of more structural cells with lower P contents, and the microbial community breaking down the lagarosiphon biomass beginning to utilise P previously released into the water column to meet their metabolic needs. TP release rates become more negative at the “collapse” stage of visual decay as cells with even lower C:P ratios were broken down. During the two final stages of decay the rate of TP release approaches zero which may indicate a slowing of the microbial communities' metabolic rate as only more recalcitrant cells remain or that the availability of P previously released into the water column was limiting microbial growth and metabolism. The more recalcitrant nature (lower C:N and C:P ratios) of the cells remaining during the later stage of decay is also evidenced by the rate of TN release hovering around zero and becoming negative during the final “dead” stage.

Conclusions

The largest releases of TN and TP from the diquat treated lagarosiphon shoots occurred from cell lyses caused by the herbicide itself and took place before there were any visible signs of decay. From this point, the size of the release generally decreased as the time-since-treatment increased, and the shoot continued to decay. These decreasing amounts and rates of TN and TP release, result from the breakdown of the remaining biomass being microbially mediated, rather than being a direct result of

the diquat application, and therefore are limited by the size of the microbial community and its rate of metabolism. Further, as the decay process progresses, cells with greater C:N and C:P ratios remain and the microbial community will utilise greater amounts of N or P they contain for their own purposes, reducing nutrient releases to the water column. In fact, the infecting microbial community may even be required to scavenge N and P from the water column to meet their metabolic needs as the decay process progresses.

Ultimately, the relationship between visual stage of decay and TN and TP release identified in this study could be used by lake managers to help assess the role of herbicide treated weed beds in fuelling algal blooms. By combining these relationships with a lake specific framework, that includes background nutrient levels, temperature, light availability and residence time, a more robust assessment of the likelihood of herbicide treated weed beds contributing to algal blooms could be established.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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