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Role of catchment litter in wetland P cycling-recent experience from Western Australia

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Abstract

Many wetlands in south-western Australia are situated in the interdunal depressions of coastal sand dunes, and have catchments with significant native vegetation. While farming and urbanisation are common sources of nutrients, natural processes such as P release from catchment litter and its potential as a P source for these waters have rarely been investigated. Such information is important not only in understanding the wetland ecology, but also in setting restoration targets for eutrophic waters in the region. This review focuses on recent works conducted in a number of small wetlands near Perth, Western Australia, covering the issues of litter production, rates of decomposition and P leaching, subsequent interactions of leachate with soil and microbial biomass, and the mobility of nutrients. The export of P from catchment litter to wetland was estimated using a new "in-lake" method, developed to quantify P transfer through primary (atmospheric and groundwater) and secondary processes (e.g. circulation and sediment-water interactions).

Key words : catchment litter, litter decomposition, P leaching, microbial P, P cycling, seasonal wetland

सारांश

दक्षिण–पश्चिम आस्ट्रेलिया की अनेकों आर्द्र भूमि समुद्र तट के बालू के टीलों के बीच के अवनमनीय क्षेत्रों में स्थित हैं। इनके जलग्रहणी क्षेत्रों में महत्वपूर्ण स्थानीय वनस्पतियाँ पाई जाती हैं। जबकि पोपकों के सामान्य स्त्रोत खेती और शहरीकरण है, कुछ प्राकृतिक प्रक्रियायें जैसे जलग्रहण क्षेत्र के कूड़ा कर्कट से फास्फोरस का मुक्त होना तथा फास्फोरस के स्त्रोत के रूप में इन जलाशयों के प्रभावों पर कदाचित ही अनुसंधान हुये हैं। इस प्रकार की सूचनायें आर्द्र–भूमि की परिस्थितिकी को समझने के लिये तो आवश्यक हैं ही साथ ही इन स्थानों के यूट्राफ़िक जल के जीर्णोद्वार का लक्ष्य बनाने में भी महत्वपूर्ण है। यह पुनर्विलोकन पश्चिमी आस्ट्रेलिया के पर्थ के छोटे–छोटे आर्द्र–भूमियों पर नवीनतम अनुसंधानों पर केन्द्रित है जिसमें, घास–फूस का उत्पादन, इनके निक्षेपण की दर और फास्फोरस का निथारन, निक्षालन का मिट्टी तथा रोगाण्वीय जीव मात्रा से अंतः क्रिया तथा पोषकों की सचलता, महत्वपूर्ण हैं.। जलग्रहण क्षेत्र के घास–फूस से आर्द्र भूमि की ओर फ़ास्फ़ोरस का निर्यात एक नवीन विधिा "इन–लेक" द्वारा अनुमानित किया गया है। उसका दिकास फ़ास्फ़ोरस के स्थानान्तरण का, प्राथमिक (वायुमंडलीय और भू–जल) तथा गौण विधियों (उदाहरर्णाथ परिचलन और तलछट जल की अंतः क्रिया) द्वारा परिमाण प्राप्त करना है।

सांकेतिक शब्द : जलग्रहण क्षेत्र का घास–फूस, घास–फूस का सड़ना, फास्फोरस का घुल कर बहना, रोगण्वीय फास्फोरस, फास्फोरस चक्र, मौसमी आर्द्र भूमि

Introduction

Many wetlands of the Swan Coastal Plain of south-western Australia have catchments with significant areas of native vegetation. These wetlands are numerous, and mostly feature poor water exchange, shallow depth, and limited open water. They potentially serve as filters or sinks which inhibit nutrient loss from the landscape during wet seasons. During the past few decades the region has seen an alarming increase in the nutrient loading and consequently the eutrophication of surface waters. The freshwater wetlands in the region are generally located in the inter-dunal depressions between coastal sand dunes, and are often P limited in relation to phytoplankton growth.

Soils in the region are built up by accumulation of marine, aeolian and alluvial sediments, and much of the upper horizons are severely leached, infertile, and typically contain low P and low organic matter[1]. The increased P in the water bodies, which has been commonly observed in past decades, has been largely attributed to human activities, such as agriculture and urbanisation[2]. Ecological studies elsewhere have shown that plant litter from fringing vegetation can serve as a primary energy and nutrient source for wetland ecosystems[3, 4, 5]. Terrestrial litter also serves as a nutrient source for downstream waters via direct litterfall, wind, run-off and seepage[6, 7]. Such a source was reported to account for over 70% of annual soil carbon flux[8]. The amount of nutrients recycled through litterfall may vary with vegetation type, catchment cover, climate and site conditions. Wetlands in southeastern USA have litterfall of 4100 to 5820 kg $ha^{-1}yr^{-1}$, with litterfall N input of 43 to 52 kg $ha^{-1}yr^{-1}$ and P of 2.2 to 2.7 kg $ha^{-1}yr^{-1}$ [9]. In the Southern Hemisphere, nutrients turnover from litterfall was reported to be 59 to 64 kg $ha^{-1}yr^{-1}$for N and 1.9 to 2.4 kg $ha^{-1}yr^{-1}$ for P in a rain forest in Australia[10]. In southwestern Australia, about 58 kg $ha^{-1}yr^{-1}$ N and 1.9 kg $ha^{-1}yr^{-1}$ P may be returned from karri (Eucalyptus diversicolor F. Muell.) forest sites in P-poor areas[11].

While farming and urbanisation are two common sources of nutrients, natural processes such as P release from woodland litter and its significance as a P source for interdunal wetlands is largely unknown. There is little attention to such natural sources of nutrients. Anecdotal evidence suggests there is a connection in P cycling between catchment and wetlands. For example wetland sediment, where there is an accumulation of organic materials, often exhibits higher P content than native soils. Such enrichment of sediment P has been observed in a number of wetlands studied near Perth[12]. In a study on the role of catchment litter in wetland P cycling, the authors observed increased soil P content from upland (woodland) to wetland, from 50 to up to >1000 g Pg^{-1} in the catchment of Thomsons lake[13]. The lowlying area, where there is an accumulation of tree litter, was found to have the highest soil P content. Such information appears to suggest that catchment litter has a role in wetland P enrichment, important not only for understanding the role of catchment liter as a nutrient source for local wetlands, but also for understanding nutrient conditions prior to human disturbance, which is critical in setting restoration targets for eutrophic waters in the region.

Catchment litter as a P source—a sediment perspective

In a study of a number wetlands near Perth, southwestern Australia, the authors found sediment total P content to be typically correlated with sediment organic matter ($R^2 = 0.94$)[12]. There is a high organic P content in sediment (average 37%), with humic-P accounting for a large proportion of total P in some lakes (up to 74%, average 20%). These data support previous findings that phosphorus associated with humic substances can be a major pool, accounting for more than half of the sediment phosphorus budget in freshwater wetlands[14, 15]. There can be two possible sources for this sediment P enrichment: 1) sedimentation of algal and plant material through internal P cycling. These wetlands are often surrounded by dense fringing vegetation, and some produce in-lake macrophytes and emergent plants, so that organic debris can be an important component of sedimentation, leading to an accumulation of humic materials on lake sediments; 2) transport of P and organic P along with organic C from external sources. Gilvin (originating from the Latin adjective 'gilvin', meaning pale yellow) is generally relevant to various heteropolycondensates of phenolic compounds (humic substances). There is evidence that gilvin is transported from wooded catchment to the wetlands[16, 17]. In 'humic-stained' waters the gilvin content (measured as g440) may reach 58 m^{-1} [18]. It is reasonable to expect nutrient transport to follow similar export pathways towards wetlands. The authors focused on studying the second possibility since it is linked to catchment litter turnover, and the relevant processes are much less known, and while internal cycling is important it can be considered as secondary processes which rely on external loading.

Litter P leaching

The authors used both field and laboratory approaches to delineate the relation between catchment and wetland processes in P cycling, and the connectivity between the two. Firstly, litterfall from common plant species were collected before the local rainy season, and examined for P leaching properties under inundated conditions. It was found that inundation of 'intact' litter for 24 hours leached 30±7.5% (95% confidence level) of the total P in litter. The leached amount increased to 46.9% of total P at 115 days of inundation. Part of the released P was incorporated into microbial biomass during the long leaching period, so modifying leachate concentrations. Using liquid chloroform 'fumigation' it was estimated that 36.2 ± 15.6% (95% confidence level) of total P leached during the 115-day inundation was in the microbial biomass pool[19]. Overall, P leaching during initial and prolonged inundation was correlated with litter Ca, Mg and total base concentration, but the initial total P concentration of litter was a good predictor of P leaching, in both short-term and prolonged inundation ($R^2 = 0.80$ and 0.93, $p < 0.0001$)[19].

The high P leaching rate during 24 hours suggests that P from litter, some sitting on the forest floor over much of the hot and dry summer, could produce a significant P flux from local catchments during early storm events of the wet season, and thus can be a potential source contributing nutrients to downstream wetlands. By a simple calculation the authors found the amount of P leached from litter via annual rainfall may equal the P held in the water column of shallow wetlands on an area (catchment)-to-area (wetland) bases[19].

However, rates of leaching and decomposition depend not only on litter quality but also on field conditions. Data derived under laboratory conditions may need to be further validated under field conditions. In south-western Australia, the most notable factors operating on a wetland catchment are probably those associated with seasonal rainfall and the resultant drying and reflooding conditions in seasonal wetlands. Some 90% of annual rainfall is concentrated in the winter months from May to October, which was found to coincide with the period of most nutrient loads transported to major rivers in the region[20]. The authors therefore examined leaflitter leaching and P release under field conditions over the wet season. Litter was collected from a few species common on the woodland catchment, flooded gum (*Eucalyptus rudis* Endl.), jarrah (*Eucalyptus marginata* Sm.), banksia (*Banksia menziesii* R.Br.) and blue gum (*Eucalyptus globulus* Labill.) and used to investigate P leaching in the field. These were tested in presence or in the absence of soil, and under inundated or non-inundated conditions. Results showed that litter P was primarily released to leachate during the first wet month (May to June), under either inundated or non-inundated conditions. Overall, 25.7-84.1% of total P in litter was released over the rainy months from May to November, but mostly during the 'first flush', which occurred in early May[21]. On the other hand, the leachate was highly yellow-coloured, especially during the 'first flush', which had total P concentration of 1.2-4.6 mg L^{-1} (non-flooded) to 1.5-5.7 mg L^{-1} (flooded).

The authors estimated gilvin leaching from litter using a "humic acid (HA) equivalent" concept, derived by drawing an analogy between the spectrophotometric properties of gilvin and those of humic acid[22]. The total amount of gilvin leached over the wet season was in the order: flooded gum > jarrah > blue gum > banksia, irrespective of 'flooded' and 'non-flooded' conditions. Leaf litter of flooded gum and jarrah can produce 8.5-14.7 (mg gilvin g^{-1} litter) via leaching over the wet season. Banksia leaves leached little gilvin under either flooded or non-flooded conditions, equivalent to 7% of that leached from the flooded gum. Thus the Eucalyptus species such as flooded gum and jarrah, common in wooded catchments in the region, appeared to be a major source of yellow coloured substances (gilvin) under annual rainfall conditions of south-western Australia.

Litter decomposition and nutrient mobility

In a parallel study the authors placed jarrah (*Eucalyptus marginata*) and banksia (*Banksia menziesii*) leaflitter at an upland (woodland) site and a wetland site along a hillslope transect, and litter weight and nutrient contents were monitored for two years to understand the rates of litter turnover and nutrient release. Decomposition of leaf litter was rapid at the commencement of the rain season but slowed rapidly in the following period, and 1/2 to 1/3 of litter weight remaining after two years. A two-substrate quality decay model was used to simulate the weight loss, which well described litter weight loss during the 2-year field decomposition ($R^2 = 0.97$-0.99). The half-lives were predicted to be 2.6-3.2 weeks (labile fraction) and 6.4-6.9 years (recalcitrant fraction) for *E. marginata*, and 1.0-1.7 weeks (labile) and 6.6-9.9 years (recalcitrant) for banksia. These predicted parameters for decomposition of the Jarrah leaves agreed with those reported in a recent study by OConnell and Mendham[23] on decomposition (2 mm mesh) of *E. marginata* leaf litter, in a location ca. 30 km east of our study site.

The loss of K, Mg and S was correlated with weight loss of litter ($R^2 = 0.77$-0.94, $p < 0.03$-0.001), and nutrient mobility was found to be K = Mg = S > Ca > P, regardless of site and species differences. The authors found a 129% increase of P mass in decomposed *E. marginata* litter and a 174% increase in banksia litter in the woodland site over a 275-day observation period, despite a significant weight loss during the period. Such data may suggest that the woodland litter can, at least temporarily, be an efficient system in retaining P, and the phenomenon was probably associated with microbial biomass development in response to the low P supply in the soils. Overall, the between-species difference (e.g. *E. marginata* vs *B. menziesii*) on decomposition was clear, while site influences on weight loss and nutrient dynamics were more subtle, and depended critically on site microclimatic conditions.

Catchment litter production

Leaf litter accounted for Ca 67% of the total litter on the woodland catchment of Thomsons lake. The authors estimated Ca. 3048 kg ha^{-1} yr^{-1} leaf litter produced on the catchment based on monthly litterfall collected using litter trays. Assuming an average litter P content of 0.5 g kg^{-1} and 60% P leached over the wet season under field conditions (which is the mean litter content for four species and leaching rates under non-flooded conditions), a simple calculation will derive 250 kg P year^{-1} leached from the 274 ha catchment of the lake. This amount would equal an increase of 250 g P L^{-1} in lake water (based on lake volume in late September, 250 ha of 0.4 m depth), if all 250 kg P were transferred to the lake.

This equals a load of 0.91 kg P ha^{-1} yr^{-1} (before export from the Catchment) in response to annual leaf litter production on this catchment[21]. Such a source was relatively small compared with fertiliser P use in agricultural soils of the region (3.1-9.8 kg P ha^{-1} yr^{-1}). However, if most of the leached P were exported eventually from the sandy catchment (in view of the low P retention capacity of the soils), it would be comparable to the potential export from diffuse agricultural sources (P loss 0.11-1.67 kg P ha^{-1} yr^{-1}) reported by Gillingham and Thorrold[24], and comparable with P exported from farmed catchments in the region (0.12-0.89 kg P ha^{-1} yr^{-1})[25]. The latter led to the significant eutrophication of a major estuary in southwestern Australia, the Peel-Harvey Estuary, during 1990s[26]. The significance of catchment litter as a P source will thus need to be accounted for not only in understanding wetland ecology, but also ecosystem restoration and management in the region.

Fate of leached P—interaction with soil

A difficult question has been related to the movement of leachate P following the onset of winter rains. The low-gradient sandy landscapes in the region have a relatively high infiltration. The critical issues relevant to P transport include the leaching and decomposition patterns of litter P, precipitation on the catchment (the main driving force of P movement), and interactions between leaching forces and factors modifying P leaching. Overall, the volumes and concentrations of P leached from surface litter can be modified during infiltration and travel through soil layers. Delineating such processes is viewed as critical for assessing the potential of P export from these wooded landscapes.

The field leaching data showed that the 'first flush' generated a mean P load of 114.7 mg m^{-2} on the wooded catchment, and P leaching was correlated with rain intensity[27]. When litter was applied to bare, sandy soil and then subjected to rain leaching, a portion of P released from litter and soil appeared to be retained through litter-soil interactions. Such interactions reduced leachate P by 25.2-29.5% and 28.6-38.6%, equivalent to a P retention of 75 mg P m^{-2} through surface application and 81 mg P m^{-2} via burial (5 cm into soil). The P retention can be attributed to increased microbial immobilisation, concurrent with an increased nutrient flux from litter. It appears that as much as 1/4 -1/3 of the P released during the current year from litter and soil would be retained in the top soil horizons under the wet season conditions.

Consequently, litter leaching in the presence of soil was found to cause a significant time-lag (about a month) in the appearance of peak gilvin load, and reduced total gilvin in leachate over the wet season.

A prior study of litter-soil interactions on this catchment showed that heterotrophic microbial biomass can capture most leached P during early rains, resulting in a three-fold increase in microbial biomass-P. About 4.8 - 43.9 mg P kg^{-1} in surface soils was retained by soil microbial biomass, leaving only about 5% of 'leachable P' in soils as compared with that held in microbial biomass[28].

P and organic C (gilvin) was also leached from the woodland soil under the litter layer, which appears to derive from residues accumulated from previous years of leaching, including those retained in and/or dried from leachate during the dry season. This may imply that retention of P and gilvin in the woodland soils is a short-term process. There is a limited capacity for P retention in these sandy soils, and the previously-retained P may be remobilised in the following rainy season, when transport is likely to continue in the direction of soil water movement and groundwater flow.

P leaching and microbial activity

A transect was established from a wetland site to an upland site in the wooded catchment of Thomsons

Lake, to examine P dynamics and microbial response to litter leaching over the rainy seasons[13, 28]. The transect passed through the lakebed, a sedge area and the riparian zone, ending in woodland on the eastern catchment of the lake. Seven sites (including one control site) were selected along the transect, which are characterised by distinctive vegetation types, plant litter, and general morphological features.

Soil chambers were deployed along the transect to measure heterotrophic microbial activity. This was measured in the field as CO_2 efflux (range 47-176 mg CO_2 m^{-2} h^{-1}), and in the laboratory as substrate-induced-respiration (SIR; range 11-133 g g^{-1} h^{-1})[23]. SIR was positively correlated with soil organic content, and was concentrated in surface soils. In contrast, in the exposed lakebed most microbial biomass was below the surface, in the 10-30 cm depth zone. There were significant changes in nutrient dynamics in response to soil microbial activity. Before rain, P extracted by anion-exchange-membrane (PAEM) was well correlated with site litter and plant debris ($R^2 = 0.95$, $p < 0.001$), suggesting that PAEM in soils was litter-sourced. This relationship was modified during the wet season: There was an overall increase in microbial biomass P (PMB; from average 7.5 to 21.6 g g^{-1}), and a decrease in PEAM / PMB (microbial biomass P) ratio in surface soils. Along the transect, the assimilation index PEAM / PMB declined towards the wetland, where soils were more silty and organic, and CO_2 production was significantly higher. The results suggest that heterotrophic microbial activity has a significant role in regulating P flux from catchment litter during the wet season, which would be likely to affect the mobility of P sourced from litter form catchment into the wetland.

The present data suggest a multi-factor regulated pathway of microbial activity on the transect. That is, litter and soil organic turnover on the catchment provided a rich resource of available P for microbial community in catchment soils. The microbial activity is reflected in soil respiration, and co-regulated by soil attributes and microclimatic factors such as moisture and temperature. The increased soil water and a small decrease in soil temperature (average 2.5-3.2°C between May and June) with the onset of the wet season responded primarily by increased microbial uptake, and consequently increased P_{MB} in surface soils and thereby lower ratios of P_{AEM} / P_{MB} along the transect[28].

The microbial P (PMB) measured in the present study was reasonably close to those reported by Grierson and Adams[29] for a jarrah forest in south-western Australia, in which microbial P varied from less than 10 in late summer to more than 50 μg^{-1} during the wet season. Overall, the onset of the wet season under the moderate temperatures of the region favours surface heterotrophic microbial activity and the transfer of bioavailable P into microbial biomass. It is still not clear how mobile are microbial biomass and PMB in soils during following rains. The extremely low PAEM in surface soils, however, means much of the soluble P has been temporarily immobilised as particulate P. The data suggested that microbial respiration and microbial biomass were particularly associated with soil litter, though questions remain concerning biomass mobility and the further turnover of microbial biomass.

Responses of soil microbial activity to soil temperature, moisture and litter leaching were examined along the same transect over the wet season. Heterotrophic respiration (CO_2 efflux) was higher in the dried lakebed and riparian areas than in upland soils, and higher during the day than at night. CO_2 efflux along the transect was positively correlated with soil moisture[30]. There were significant variations in CO_2 efflux with time of sampling, largely caused by the effect of temperature. The addition of litter leachate significantly increased CO_2 efflux especially in soils from upland sites, which had lower moisture and nutrient contents. There was a difference in response of microbial respiration between upland soils and wetland sediments to litter leachate and the wetter, warmer conditions. In general, litter leachate enhanced heterotrophic microbial respiration, and more significantly under warmer conditions (31 °C). The fungal to bacterial ratio was 2.9-3.2 for surface litter and 0.7-1.0 for soils, suggesting fungal dominance in heterotrophic respiration of surface litter, but increased bacterial dominance in soils, especially in exposed sediments in the lakebed.

Transport of litter P to wetland

There are two possibilities for transferring catchment litter, and for litter to act as source of P in wetland P cycling. Firstly, the transport may be effected via direct litterfall and/or transport via decomposing organic debris, which can be realised by wind force and surface runoff. Nutrients such as P may also be exported via solubilised or mineralised components, carried by water from the catchment, via either surface or subsurface flow.

The transport of litter P during winter rains can be more complicated due to 1) a general lack of surface runoff on these low-gradient sandy landscapes; 2) time-variable interactions between leaching and factors modifying P concentration in the leachate, such as intermittent wetting and drying, and microbial activity[28]. Overall, in the absence of surface runoff the P leached from surface litter may be modified during infiltration and transport through soil matrices. It is therefore difficult to directly relate the amount of P released on the catchment to what is received by the wetland because of the unknown portion recycled within the catchment itself. Meantime, as mentioned above, the previously-retained P in the soil matrix may be remobilised in the following rainy seasons, and the overall traveling routes of leachate will be continued in the direction of the wetland depression.

With respect to aquatic ecology, it is important to ascertain the amount of nutrients received by the aquatic volume. To avoid transport complications and any biotic and any abiotic transformations that take place before nutrients reach the receiving waters, the authors developed a simple, in-lake approach to quantify influences of the key processes controlling water column P concentrations in shallow lakes[31].

The method involves using a field experimental design employing various types of transparent plexiglass columns (chambers) pushed into sediments, followed by synchronized monitoring of P concentrations within and without (outside) the chambers. Various processes including 1) mixing and circulation; 2) atmospheric input including dry fall and wet precipitation, and wind transport from adjacent areas; 3) groundwater, including upward subsurface flow; 4) sediment release or sedimentation can be partitioned and quantified in terms of their contributions to water column P (as total P, $\mu g\ m^{-2}\ d^{-1}$), based on a simple deductive method[31].

The method was applied at nearshore and offshore sites in Thomsons Lake. Atmospheric and groundwater inputs were found to be the two main processes contributing to P loadings to the wetland (1233 and 1010 μg P $m^{-2}\ d^{-1}$), but their influence was restricted to near-shore sites. Such findings are consistent with the groundwater transport pattern in wetlands of the region, i.e. shallow groundwater (more carbon or nutrient enriched) being transported to near shore areas while deeper groundwater flows to middle of the wetland[32]. The estimated influence on total P by mixing-circulation, atmosphere and groundwater were 2.4-25 times higher near the lake margin as compared with an offshore site. The wooded catchment studied here is in a nature reserve with little human pollution, and so P reaching the lake may be regarded as from catchment litter turnover. As this source is large and diffuse, it could well be the 'major' source of P in unfertilised landscapes, such as the severely leached wetland catchment studied here.

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