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Soil C, N and P stoichiometry of *Deyeuxia angustifolia* and *Carex lasiocarpa* wetlands in Sanjiang Plain, Northeast China

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Abstract

Purpose The theory of ecological stoichiometry has improved understanding of nutrient circulation processes in ecosystems. The purpose of this work was to study ecological stoichiometric characteristics of carbon, nitrogen and phosphorus in wetland soils of Sanjiang Plain, northeast China.

Materials and methods A *Deyeuxia angustifolia* wetland (swamp meadow) and a *Carex lasiocarpa* wetland (marsh) were chosen for collection of soil cores (0–30 cm depth). Soil organic carbon, total nitrogen and phosphorus were analyzed to study patterns of C/N (R_{CN}), C/P (R_{CP}), N/P (R_{NP}), and C/N/P (R_{CNP}) in wetland soils.

Results and discussion Soil carbon, nitrogen and phosphorus stoichiometry differed between the two wetlands. Soil R_{CN} (0–30 cm depth) in the *D. angustifolia* wetland was close to that in *C. lasiocarpa* wetland (12.97 and 12.80, respectively), but R_{CP} and R_{NP} in *C. lasiocarpa* soils were significantly higher than those in *D. angustifolia* soils. R_{CN} changed little within soil profile, without obvious trends in both wetlands. Both R_{CP} and R_{NP} decreased with depth from the surface, and both R_{CP} and R_{NP} were higher at every depth interval in *C. lasiocarpa* soils compared to *D. angustifolia* soils. R_{CN} in surface soil (0–10 cm, organic-rich “Lo” layer) was not significantly different from R_{CN} in the entire profile (0–30 cm, “La layer”) of *D. angustifolia* wetland, while R_{CP} and R_{NP} were both significantly different between the Lo and La layers. In *Carex lasiocarpa* wetland, R_{CN}, R_{CP} and R_{NP} in Lo layer were significant higher than those in La layer. R_{CNP} in La layer of *D. angustifolia* and *C. lasiocarpa* wetlands were 65:5:1 and 163:13:1, respectively.

Conclusions Soil R_{CN} was relatively consistent, while R_{CP} and R_{NP} reflected P limitation in wetlands of Sanjiang Plain. Further research is needed to determine whether these ratios hold among other wetland ecosystems.

Keywords *Carex lasiocarpa* · *Deyeuxia angustifolia* · Ecological stoichiometry · Sanjiang Plain · Wetland soil

1 Introduction

All matter is composed of chemical elements in different ratios, from cell to the individual, from ecosystems to the biosphere (Michaels 2003). Carbon, nitrogen and phosphorus are the three main elements that exist in relatively stable ratios in living organisms, and key characteristics of organisms and ecosystems are determined by dynamics of element ratios (Michaels 2003). Chemical components in living beings interact with those in the inorganic environment. Element ratios in environments affect those of organisms in that environment, while organisms also affect the elemental composition of their environments by absorbing or releasing elements in ratios that are different from ambient ratios (Elser and Urabe 1999). In order to reveal whether there are unifying characteristics for all matter, ecological

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stoichiometry theories are developed to link elemental chemical processes with structure, processes and functions of ecosystems at the macro scale (Elser et al. 2000; Sterner and Elser 2002; Zeng and Chen 2005; He and Han 2010).

Redfield (1958) reported that planktonic biomass contains C, N, and P in a comparatively steady atomic ratio of 106:16:1, similar to the proportions of C, N, and P in marine water, and this chemical relationship was named the "Redfield ratio". Redfield's observation catalyzed advances in research on nutrient biogeochemical cycles, much of which focused on nutrient ratios in plants and marine ecosystems. Numerous stoichiometric studies have been conducted in terrestrial ecosystems as well, particularly in grassland and forest systems (Elser and Hassett 1994). McGroddy et al. (2004) reported that R_{CNP} in plant rootlets was 1157:24:1 at global scale. Han et al. (2005) reported a R_{NP} ratio of 15.3 in grass leaves, based on a study of 213 plant species in China. In plant tissues and litter, R_{CN} is generally>100 (Zeng and Chen 2005). Some research on nutrient characteristics of animals and microorganisms found a R_{CN} of 6 in bacteria, indicating that many animals and microbes exist in environments that are abundant in carbon but limited in N in relation to their nutritional requirements (Vitousek et al. 2002). Compared to abundant researches on element stoichiometry in plants and aquatic ecosystems, less attention has been paid to terrestrial ecosystems, in particular to R_{CNP} ratios in soil.

Soil is very heterogeneous. Climate, hydrologic regime, vegetation, geomorphology, parent material and biology all effect soil formation and development processes; element transport and geochemical circulation in Earth's crust results in more complex stoichiometric dynamics for C, N, and P in terrestrial soils than in marine environments (Kaye et al. 2003; Mulder and Elser 2009; Taylor and Townsend 2010). Cleveland and Liptzin (2007) found remarkably consistent R_{CNP} ratios in soils and biomass — 186:13:1 and 60:7:1, respectively, at the global scale — and concluded that a relationship existed between C, N and P in soils, similar to the concept of the Redfield ratio. Tian et al. (2010) reported that soil R_{CN}, R_{CP}, and R_{NP} in China were 11.9, 61 and 5.2, respectively, and that the R_{CNP} ratio was consistent at 60:5:1. They also found that C, N, and P stoichiometry in soil was affected by climate zones, soil depth and degree of weathering of parent materials. The spatial variability, influencing factors and geographical interpretation of R_{CN}, R_{CP}, and R_{NP} ratios in soils remain to be clarified.

Wetlands are transitional region between aquatic and terrestrial ecosystem. Wetland soils are hotspots for biogeochemical cycling (Kaye et al. 2003; Mulder and Elser 2009). C, N and P are the three elements of major concern in freshwater wetland ecosystems, but there are few studies on C, N and P stoichiometry in wetland soils. Our objectives in this study are to: (1) examine R_{CNP} stoichiometric characteristics in typical swamp meadows (*Deyeuxia angustifolia* wetland) and marshes (*Carex lasiocarpa* wetland) in Sanjiang Plain, Northeast China; (2) characterize R_{CN}, R_{CP} and R_{NP} distribution patterns in wetland soil profiles; (3) examine how R_{CN}, R_{CP} and R_{NP} vary according to hydrologic regimes and depth in soil profiles. Based on these three objectives, we compared R_{CN}, R_{CP} and R_{NP} ratios in Chinese wetlands to ratios reported for other geographic regions, in an attempt to determine whether a consistent R_{CNP} ratio exists in wetland soils worldwide.

2 Methods and materials

2.1 Study area

The Sanjiang Plain averages 55 m above sea level and is located in China's sub-humid warm temperate continental monsoon climate zone, with mean annual precipitation of ~558 mm with substantial interannual and seasonal variations (Guo et al. 2010). The Sanjiang Plain contains the largest area and most common type of freshwater wetland in China. Three dominant wetland types — permanently inundated wetland, seasonally inundated wetland and shrub swamp — comprise 56.9 %, 22.6 % and 20.5 %, respectively, of wetland areas in the Sanjiang Plain. *D. angustifolia* wetland is the typical seasonally inundated swamp meadow and *C. lasiocarpa* wetland is the typical permanently inundated marsh (Yu et al. 2007; Song et al. 2009). *D. angustifolia* is a perennial, cold-temperate mesophyte that grows in high floodplains, the first terrace or edges of depressional wetlands, and has a broad ecological adaptation to water. *D. angustifolia* is the dominant plant species in the seasonally inundated swamp meadow, occupying 90–95 % of total plant cover. Other species in the swamp meadow include *Stachys baicalensis*, *Lythrum salicaria* and *Phragmites australis*. *C. lasiocarpa* is a perennial sedge, and a typical clonal plant of rhizomatous Cyperaceae family. *C. Lasiocarpa* commonly grows in depressional areas with persistent surface water within 30–50 cm depth.

In August 2011, we collected soil samples from the Sanjiang Experiment Station of Wetland Ecology, Chinese Academy of Sciences (47°35′17.8″N, 133°37′48.4″E) (Fig. 1). In *D. angustifolia* and *C.lasiocarpa* wetlands, three soil cores (0–30 cm depth; named La layer) were collected from each site. The albic soil layer is found within 30 cm of soil surface in *D.* wetland, while the albic soil is generally found in 50-cm depth or deeper layers in *C. lasiocarpa* wetland (Zhang et al. 2008). Soil cores were sectioned in the field into 2-cm increments and the top 0–10 cm was an organic-rich layer (named Lo layer). Soil samples were sealed in polythene bags and brought back to laboratory. Increments were air dried at 70 °C, weighed for bulk density, ground, and sieved through a 2-mm nylon mesh, then

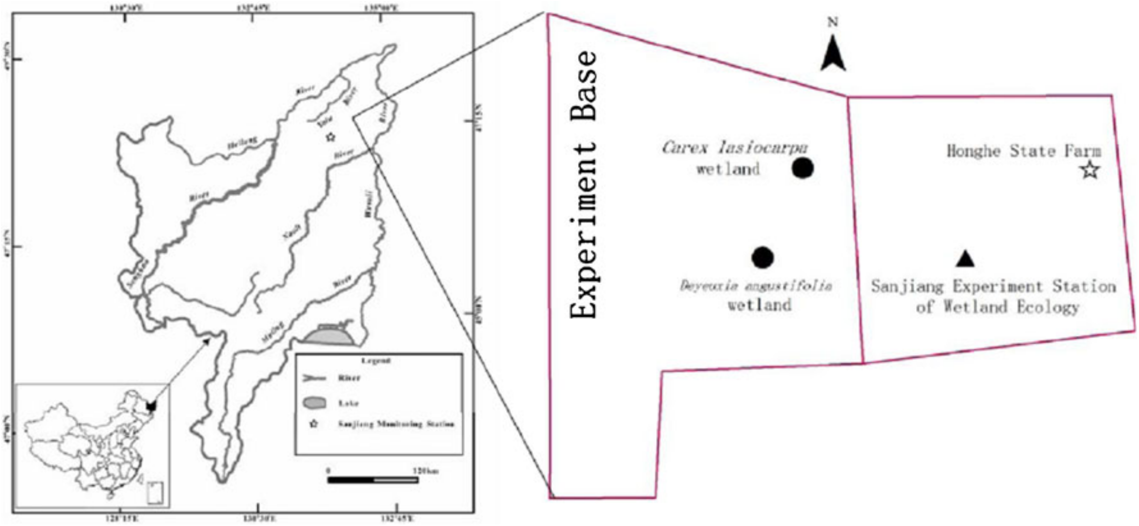

Fig. 1 Location of study area

analyzed for organic C, total N and total P. Bulk density was calculated from dry weight per unit volume for each depth increment (Craft and Loomis 2010).

2.2 Chemical analysis

Soil organic carbon was measured by the $K_2Cr_2O_7$-H_2SO_4 oxidation method (Zhang et al. 2009), total soil nitrogen (TN) was measured using the Kjeldahl digestion procedure (Gallaher et al. 1976), and total soil phosphorus was measured by the Mo–Sb Antispectrophotography method (Wang et al. 2006). During the analysis, all samples were analyzed in parallel and blank tests were performed to assure accuracy and precision. Results from replicate tests produced differences within 0.5 %, 0.1 %, and 0.005 % for soil organic carbon, total nitrogen and total phosphorus, respectively. All glass bottles used were soaked in 3 mol l^{-1} HNO_3 solution, washed with deionized water and oven dried before use.

2.3 Statistical analysis

Weighted averages calculated by soil bulk density and atomic weight were used to determine atomic ratios of C, N, and P for each soil increment and the Lo and La layers. R_{CN}, R_{CP}, R_{NP} and R_{CNP} are reported as atomic mole ratio. Differences in R_{CN}, R_{CP} and R_{NP} among soil layers and wetland types were evaluated using variance of analysis (ANOVA) with least square difference (LSD) using SPSS 10.0 Software (SPSS Inc., Chicago, IL). Correlations between C, N and P in soil were calculated for each wetland type using Pearson's correlation test with a 95 % confidence interval.

3 Results

3.1 C, N and P stoichiometry in different wetland soil

R_{CN}, R_{CP} and R_{NP} in Lo layer averaged 12.97, 161.96 and 5.04 in *D. angustifolia* wetland soil, and 12.80, 161.96 and 12.75 in *C. lasiocarpa* wetland soil, respectively (Table 1). R_{CN}, R_{CP} and R_{NP} in La layer averaged 13.70, 116.79 and 8.50 in *D. angustifolia* wetland soil and 17.10, 365.94 and 21.43 in *C. lasiocarpa* wetland soil, respectively. There were no significant differences in R_{CN} among soil layers, while R_{CP} and R_{NP} were significantly different between Lo and La layers of *D. angustifolia* wetland soil ($F=21.184$, $p=$

Table 1 Summary of soil C, N and P ratios in Sanjiang Plain

Wetlands	Depth	Sample numbers[a]	R_{CN}[b]	R_{CP}	R_{NP}	R_{CNP}
D. angustifolia	La	15	13.70±1.19	116.79±16.39	8.50±0.45	117:9:1
	Lo	45	12.97±0.87	64.78±10.70	5.04±1.10	65:5:1
C. lasiocarpa	La	15	17.10±1.16	365.94±46.68	21.43±2.73	366:21:1
	Lo	40	12.80±1.45	161.96±38.21	12.75±3.08	163:13:1

[a] Three soil profiles were at 30 cm depth in *D. angustifolia* wetland, and were 30, 24 and 26 cm depth in *C. lasiocarpa* wetland

[b] Values are weighted means ± SE

0.010; F=25.657, p=0.0017). R_{CN}, R_{CP} and R_{NP} were significantly different between Lo and La layers of *C. lasiocarpa* wetland soil (F=16.069, p=0.016; F=34.305, p=0.004; F=13.323, p=0.022).

R_{CN}, R_{CP} and R_{NP} in Lo layers of these two wetlands were significantly different (F=16.069, p=0.016; F=34.305, p=0.004; F=13.323, p=0.022). R_{CP} and R_{NP} in La layers of these two wetlands were significantly different (F=17.998, p=0.013; F=16.611, p=0.015) while R_{CN} was not. R_{CNP} in Lo and La layers were 117:9:1 and 65:5:1 in *D. angustifolia* soil, and 366:21:1 and 163:13:1 in *C. lasiocarpa* soil.

3.2 Distribution patterns of C, N and P stoichiometry in different wetland soil

In *D. angustifolia* wetland profile, R_{CN} changed little with no obvious distribution rules from surface to bottom. The highest R_{CN} value, 15.54, appeared at 0–2 cm depth and the lowest R_{CN} value, 10.37, appeared at 28–30 cm depth. R_{CP} and R_{NP} showed the same distribution trends, decreasing with increasing soil depth. R_{CN} decreased from 165.04 at 0–2 cm to 16.01 at 28–30 cm, while R_{NP} decreased from 10.52 to 1.59 over the same interval (Fig. 2).

In *C. lasiocarpa* wetland profile, R_{CN} showed a decreasing trend, with the highest value (19.15) was at 0–2 cm and the lowest value (8.56) at 26–28 cm. R_{CP} and R_{NP} decreased sharply from surface to mid profile (from 787.98 to 146.95 for R_{CP} and from 37.80 to 13.54 for R_{NP}). Ratios of R_{CP} and R_{NP} changed little from 12 to 30 cm depth.

R_{CN} showed little difference within soil profiles of *D. angustifolia* and *C. lasiocarpa* wetlands, but both R_{CP} and R_{NP} were higher for all depth increments in *C. lasiocarpa* wetland than those of *D. angustifolia* wetland.

3.3 Correlation analysis of C, N and P in wetland soil

C is generally closely related to N in soil. Plants absorb nitrogen from soil and CO_2 from atmosphere to sequester solar energy via photosynthesis. As plants die, microorganisms decompose litter to obtain energy and nutrients, and C is returned to the atmosphere in the form of CO_2 or CH_4 (Melillo et al. 1989; Cambardella and Elliott 1992). Correlation analysis suggests that there are significant positive correlations between C, N and P in *D. angustifolia* and *C. lasiocarpa* wetland soils (Table 2).

In these two wetland types, in both Lo and La layers, there was a significant positive correlation between C and N. However correlations between N and P differed among wetland types and soil layers. In *D. angustifolia* wetland, N was not significantly related to P in Lo layer, but was in La layer. In *C. lasiocarpa* wetland, N was not significantly related to P in either Lo or La layer. This difference might reflect effects of hydrologic regimes and microorganisms on P circulation in wetlands. P mainly becomes available through weathering of soil parent materials, and from litter decomposition in natural wetlands, and is easily leached from inundated soils. The water table is below soil surface in *D. angustifolia* wetland, and decomposition of litters is a predominately aerobic process. P released during decomposition was easily leached from soils where the albic layer appeared in the wet season, so the N–P relationship was weak in Lo layer but significant in La layer. But surface water is present all year in *C. lasiocarpa* wetland, and P may be taken up by microorganisms in Lo layer for incorporation into adenosine triphosphate (ATP) for anaerobic respiration, resulting in statistically significant N–P relationships in both Lo and La layers.

4 Discussion

Redfield (1958) found that atomic ratio of R_{CNP} in marine planktonic biomass was relatively consistent, and the ensuing "Redfield ratio" improved scientific understanding of nutrient biogeochemical circulation in marine ecosystems, while also opening an avenue of exploration for terrestrial ecosystems (Taylor and Townsend 2010). Some research

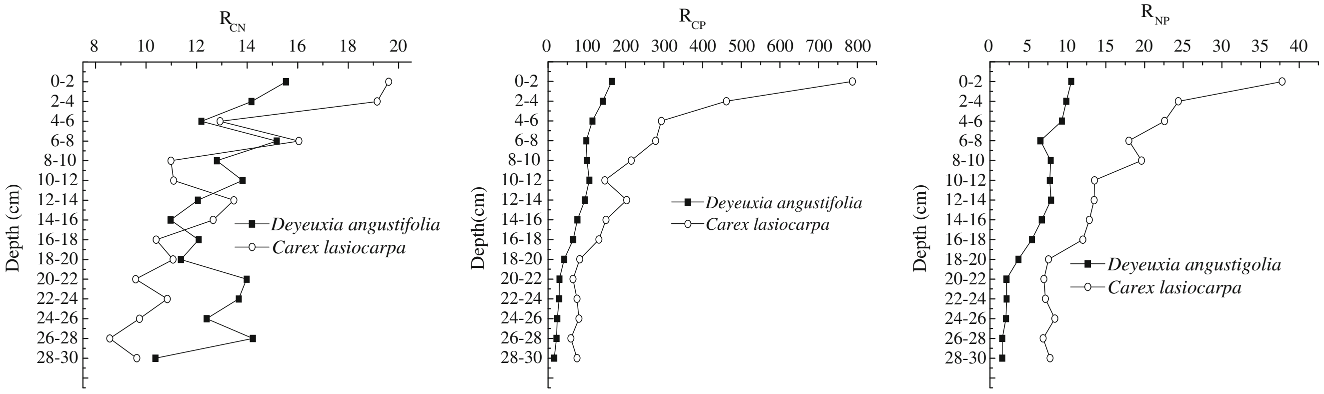

Fig. 2 R_{CN}, R_{CP} and R_{NP} profile distribution in *D. angustifolia* and *C. lasorcarpa* wetland

Table 2 Correlation coefficients of C, N and P in wetland soil

Wetlands	Independent-dependent variables	Lo	La
Deyeuxia angustifolia	C–N	0.872^{**}	0.971^{**}
	C–P	−0.039	0.537^{**}
	N–P	0.090	0.547^{**}
Carex lasiocarpa	C–N	0.925^{**}	0.934^{**}
	C–P	0.383	0.631^{**}
	N–P	0.533^{*}	0.793^{**}

$^{*}p<0.05$; $^{**}p<0.01$

has implied that there is also a “Redfield ratio” in terrestrial plants. Cleveland and Liptzin (2007) reported that R_{CNP} ratio in soil (186:13:1 from 0 to 10 cm depth) may be consistent at global scale, with corresponding ratios, of 14.31, 186 and 13 for R_{CN}, R_{CP} and R_{NP}, respectively. Tian et al. (2010) reported R_{CN}, R_{CP} and R_{NP} ratios of 14.4, 136 and 9.3 in Chinese surface soils (0–10 cm depth), and 12.1, 61 and 5.0 deeper in soil profile (as deep as 250 cm for some soil profiles).

In our studies, R_{CN} in *D. angustifolia* wetland soil and in La soil of *C. lasiocarpa* wetland were close to results mentioned above, which supports Cleveland and Liptzin’s hypothesis (2007) that R_{CN} in soil is comparatively consistent. Though R_{CNP} varies greatly with soil depth in results reported by various researchers, R_{CN} is consistently in the range of 12–20, indicating that there may be a “Redfield ratio” for R_{CN} in soils at the regional or global scale. However, at smaller scales or in specific environments, soil profile depth has a substantial effect on R_{CN}. In the present work, R_{CN} in Lo layer of *C. lasiocarpa* wetland was 17.0, which was significantly higher than that of La layer, indicating that while R_{CN} may be relatively stable at large spatial scales, a large degree of heterogeneity exists at the local scale. Few studies report effects of soil depth on C, N and P stoichiometry when calculating R_{CN}. Therefore a key problem is to establish a uniform soil profile depth at which the R_{CN} value will be universally meaningful, and that will facilitate comparisons between studies.

R_{CP} in Lo and La layers of *D. angustifolia* wetland were lower than those reported for global or China soil. R_{CP} in La layer of *C. lasiocarpa* wetland was close to that in global and China soils, but R_{CP} in Lo layer was much higher. R_{NP} in *D. angustifolia* wetland soil was lower than that in global and China soil while R_{CN} in *C. lasiocarpa* wetland soil was much higher. Vegetation types, biomass and nutrient distribution in plant tissues might influence R_{CNP} in soil at the site scale in addition to hydrothermal conditions and soil formation. R_{CP} and R_{NP} were more readily affected by complexities of P biological circulation in wetlands studied here. In *C. lasiocarpa* wetland, persistent surface water and anaerobic conditions facilitate leaching of P leaching from surface soil (Liu et al. 2006), resulting in high values for R_{CP} and R_{NP}. In *D. angustifolia* wetland, no surface water is present, so there is likely greater P retention, which leads to comparatively higher R_{CP} and R_{NP} values compared to *C. lasiocarpa* wetland.

Koerselman and Meuleman (1996) reported that when R_{NP} in plants was greater than 16, ecosystems were limited by P, when R_{NP} was less than 14, ecosystems were limited by N, and when R_{NP} was in range of 14–16, ecosystems were not limited by either P or N. Other researchers found R_{NP} of 31.32 and 26.37, respectively, in leaves and roots of *C. lasiocarpa* (He and Zhao 2001), and 24.56 and 11.95, respectively, in leaves and roots of *D. angustifolia* (Sun et al. 2011). These results suggest that root growth of *D. angustifolia* was not limited by P. *D. angustifolia* was more greatly restricted by N while *C. lasiocarpa* was more substantially restricted by P. R_{NP} in leaves and roots of these two plants were similar to the R_{NP} in soil.

Differences in R_{CP} and R_{NP} among *D. angustifolia* and *C. lasiocarpa* wetland soil in the present work are consistent with the conclusion that R_{NP} increases with increasing growth rates of vegetation. In general, growth rates of the hydrophyte were higher than those of terrestrial plants, resulting in greater P uptake by the hydrophyte. In addition, differences in hydrologic regime in these two wetlands might support the deduction that R_{CP} or R_{NP} in *C. lasiocarpa* wetland soils are influenced by leaching, particularly in surface soil. In *C. lasiocarpa* wetland, permanent surface water could cause P to leach downward, and result in very high R_{CP} and R_{NP} in surface soils. In *D. angustifolia* wetland, surface water is seasonal and vertical P migration appeared to be weak, with the consequence of relatively low R_{CP} and R_{NP}.

In natural wetlands, P availability to plants comes mostly from weathering of soil parent materials and from litter

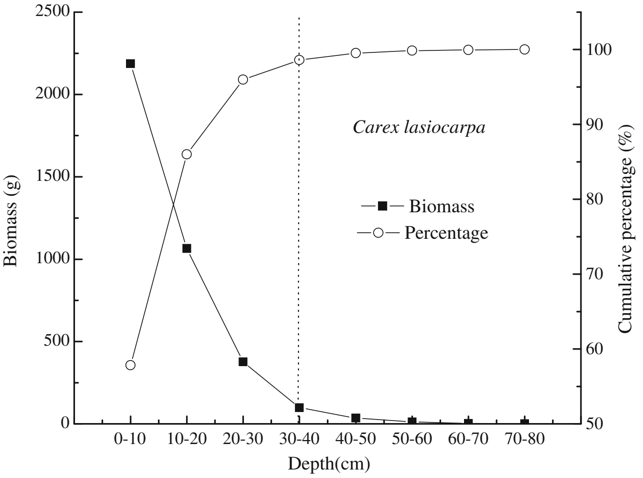

Fig. 3 Distribution characteristics of underground biomass of *C. lasiocarpa* (He 2003)

decomposition (Wu et al. 2009). In addition to various degrees of leaching caused by different hydrologic regimes, N and P allocation to different tissues of *C. lasiocarpa* and *D. angustifolia*, biomass distribution in different soil layers, soil organic matter decomposition rates and variations in soil fauna and microorganisms may all affect R_{NP} in soils of wetlands studied here. It was reported that over 95 % of *C. lasiocarpa* underground biomass was distributed in the upper 30 cm of soil (Fig. 3) and that underground biomass in soil layers below 50 cm could be neglected (He 2003). N or P distribution among different plant tissues was ranked as rootlets>rootstock>leaves>standing litter. N and P storage in *C. lasiocarpa* tissues were determined to be 20.43 and 1.71 g m^{-2}, respectively, in rootlets, 7.32 and 1.02 g m^{-2} in rootstock, 1.77 and 0.12 g m^{-2} in leaves, 0.19 and 0.02 g m^{-2} in standing litter (He and Zhao 2001). According to these results, N and P are mostly stored in rootlets and rootstock in *C. lasiocarpa* while N and P storage in leaves and standing litters, which were the main feedback routes of *C. lasiocarpa* to soil, were limited and comparatively low. A small amount of P was returned to soil via leaching during litter decomposition processes of *C. lasiocarpa*, while most was stored in roots.

5 Conclusions

In summary, wetland soils are often saturated or characterized by high moisture content. Variability in soil moisture content will result in different vertical and horizontal distributions of C, N and P, reflecting differences in nutrient uptake by plants and litter decomposition by microorganisms. Nutrient stoichiometry in wetlands is particularly influenced by P limitation in surface wetland soils. Although some conclusions have been drawn from present work, further research is needed to determine roles of R_{CN}, R_{CP} and R_{NP} in ecosystem functioning of these two different wetlands. Factors influencing nutrient stoichiometry in wetlands are not entirely resolved, although vegetation, hydrologic regime and decomposition processes play important roles.

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