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Dynamic characteristics of soil properties in a *Robinia pseudoacacia* vegetation and coastal eco-restoration

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ABSTRACT

Precipitation is one of the major determinants of soil moisture in plantations growing in the saline-alkali soil in the Yellow River Delta. The present study was conducted on a 28-yr old *Robinia pseudoacacia* plantation, a major vegetation type of the Yellow River Delta, and the results indicated strong seasonal patterns in soil moisture, salt, nutrient and enzyme activities at varying depths with respect to annual precipitation. Soil moisture during the growing season of March to October fluctuated drastically in response to precipitation events and was generally higher than that from November to February. Furthermore, soil water content in the 0–60 cm soil layer was positively correlated with precipitation during the same period but not for the value in the 60–80 cm soil layer. Salt content in different soil layers increased gradually from November to February, decreased from February to September and then increased in October. Precipitation was strongly and negatively correlated with soil salt content in different soil layers (except 20–40 cm). Soil enzymes became less active and soil nutrient contents decreased with soil depth, though different enzymes and nutrients showed seasonal variations. The activity of polyphenol oxidase increased in spring, reached the maximum values in June, and decreased in later months. The activity of alkaline phosphatase, proteinase and urease fluctuated throughout the growing season, with the maximum values in October. Available phosphorous increased in the early months and decreased after August, whereas available potassium, hydrolysable nitrogen and organic substances content in soil gradually increased throughout. Therefore, it is suggested that precipitation is the crucial limiting factor to tree growth through impacts on soil moisture, salt, nutrient and enzyme activities in saline-alkali soils in the Yellow River Delta.

1. Introduction

The Yellow River Delta is one of the most representative estuary wetland ecosystems with active land-ocean interactions in the world. *Robinia pseudoacacia* plantation started in the 1970s and 1980s in the maximum area arbor forest, exerting notably ecological function in this region. However, started from 1990, *R. pseudoacacia* plantation gradually showed the withering tree top and even the sheet death. Many researchers have studied canopy health (Liu et al., 2008), soil water storage ability (Xia et al., 2009) and soil physico-chemical properties (Zhang and Xing, 2009; Sun et al., 2006) on this forest. Precipitation is one of the major determinants of soil moisture in plantations growing in this area. However, it is still unclear the impacts of precipitation on dynamic characteristics of soil properties in the *R. pseudoacacia* plantation.

Soil characteristics have a vital impact on the ecosystem restoration (Toktar et al., 2016). Soil enzymes are the main mediators of soil biological processes because of their intimate relationship to organic matter degradation, mineralization and nutrient cycling (Marx et al., 2001). For example, polyphenol oxidase plays a role in the process of conversion of aromatic organic compounds to humus in soil. Catalase enhances oxidization of compounds using H_2O_2 in soil. Phosphatase hydrolyzes compounds of organic phosphorus

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and transforms them into inorganic forms for plants. Proteases are mainly responsible for hydrolyzing soil proteins into peptides and amion acids. Urease catalyses the hydrolysis of organic nitrogen to inorganic forms, which is from urea-type substrates to ammonia or ammonium ion. Invertase catalyses the hydrolysis of sucrose to glucose and fructose, and is linked to the soil microbial biomass.

Soil enzymes are produced by plants, animals and microorganisms (Zornoza et al., 2006). Their activities have been proposed as appropriate indicators of soil quality due to their high sensitivity to disturbance (Zornoza et al., 2006; García-Ruiz et al., 2008; Hendriksen et al., 2015). Soil moisture is an important determinant factor for soil enzyme activities (Henry, 2013). With the increase of soil moisture, enzyme potential activities increase (Baldrian et al., 2013; ÁBear et al., 2014). Whereas, Acosta-Martinez et al. (2011) reported high enzyme activities in drought soil. This can be explained with the report that under waterlogging condition, enzyme activities were impeded (Kang and Freeman, 1999). Variations on precipitation have been suggested to possess significant effects on enzyme activities (Munson et al., 2010; Ladwig et al., 2015). Salinity also has a powerful influence on soil enzyme activities. The increase of salinity decreases soil enzyme activities (Saviozzi et al., 2011; Pan et al., 2013). On the contrary, Morrissey et al. (2014) found salinity increase enhanced enzyme activity due to the increase of bacterial abundance in tidal wetlands. However, not all enzymes were sensitive to salinity (Saviozzi et al., 2011; Pan et al., 2013). Soil nutrients are positively correlated with enzyme activity (Pan et al., 2013; Burke et al., 2011), such as soil organic matter (García-Ruiz et al., 2008; Hendriksen et al., 2015). However, few studies were carried out to explore the impact of precipitation on soil moisture, salt, nutrient and enzyme in the coastal saline-alkali soil.

Soil salinity and water are two dominant factors on plant distribution in the Yellow River Delta (Yu et al., 2012). This area suffers greatly from soil secondary salinization and insufficient precipitation, demonstrating a high evaporation-precipitation ratio. Moreover, the decreases of freshwater supply from the yellow river in recent decades and intense human activities have significantly changed the original conditions in this area (Cui et al., 2010). Therefore, the main fresh water source of the coastal saline-alkali soil is from the precipitation and it determines the *R. pseudoacacia* forest survival and growth in this area. As the productivity decline of the *R. pseudoacacia* forest arose in recent decades, its protective functions have dropped significantly. To elucidate the decline mechanism of *R. pseudoacacia* plantation and recover its ecological functions in the Yellow River Delta, the study objectives were designed to explore soil moisture, salt, nutrient and enzyme seasonal change and examine the interactions among them and the impact of rainfall on them.

2. Materials and methods

2.1. Study area

The Yellow River Delta is the youngest land in China, which is located at the entrance of the Yellow River to the Bohai Sea. The secondary salinization is severe because of shallow groundwater, high total dissolved solid and sea water intrusion. The study was conducted at the Production base of Jinan Military Region in the Yellow River Delta (37°49′36.4″N, 118°46′37.1″E). The experimental site has a typical monsoon climate. The annual mean temperature is 12.3 °C, and the minimal and maximum temperature varied from −23.3 °C to 41.9 °C. The frost-free period is 210 days with an effective accumulated temperature of about 4300 °C. The average annual precipitation is 555.9 mm, with nearly 70% of the precipitation falling in summer (June to August). The average annual evaporation is 1962 mm, and 51.7% of annual evaporation occurs in the spring. Saline soil are the dominate soil types in the study area. Soil salt content range is 1.0‰-2.6‰ and pH range is 6.79–8.87. Groundwater level is approximately 1.5 m. The main vegetation in the delta includes *Phragmites australis*, *Suaeda salsa* and *Tamarix chinensis*. The experimental forest is pure *R. pseudoacacia* tree which was established in 1980s by planting nursery-raised one year old seedlings at a spacing of 2.5 m × 3 m. At present, the preservation rate of this plantation is 78%.

2.2. Experimental design

Three plots were established at typical pure *R. pseudoacacia* forest. The size of the sample plots was 30 m × 30 m. Six soil samples were collected randomly from each plot using a soil core cutter (diameter, 7.5 cm) for 0–80 cm soil depth at 20 cm intervals. Soil water content and salt content in different depths were monitored every month from November of 2007 to October of 2008. Furthermore, six soil samples of *R. pseudoacacia* forest in each plot were collected separately using soil core cutter from 0 to 20 cm and 20–40 cm in April, June, August and October of 2008. The soil samples of the same depth were mixed. The soil samples were placed in sealed plastic bags and taken to the laboratory. Some fresh soil samples were preserved at 4 °C for measurement of enzyme activity. Another portion was used for soil parameter analyses.

2.3. Soil moisture, salinity, enzyme and nutrient analysis

Soil moisture was determined gravimetrically by weighing and drying in an oven at 105 °C for 12 h. Some soil samples was air-dried and used for determining soil electrical conductivity (EC). EC was measured using a conducting meter (DDSJ-308, Shanghai, China) in a 1:5 soil-water extract. A portion of soil samples was air-dried and sieved to 0.25 mm to measure available phosphorus, available potassium, hydrolysis nitrogen and organic matter.

Soil enzyme activities were measured as described by Guan. All enzyme activities were determined from wet samples. The polyphenol oxidase activity was measured by gallnut method. The catalase activity was measured by potassium permanganate titration method. The alkaline phosphatase activity was expressed on a soil dry weight by correcting for water content in the soil at the time the sample was removed from the incubation bottle and is given in units of mg *p*-nitrophenol produced g^{-1} soil h^{-1}. The protease activity was measured by the method that gelatin was turned into glycin in phosphate buffer (pH = 7.4). The urease activity was determined by the method that urea was turned into NH_3 in citric acid buffer (pH = 6.7). The invertase activity was measured by the methods for the formation of glucose by sucrose hydrolysis.

Soil organic matter was measured by the $K_2Cr_2O_7$-H_2SO_4 oxidation method of Walkey and Black. Hydrolysis nitrogen was measured by the alkaline diffusion method, and available phosphorus was measured by the Bray method (Institute of Soil Science, Chinese Academy of Sciences, 1978). Available potassium was measured by flame photometry method (Worth, 1985). Precipitation data was provided by Hekou district meteorological station of Shandong Province, China.

2.4. Data analysis

Soil water content, salt content, enzyme activities and nutrient were tested by using a two-way ANOVA. Least-significant difference (LSD) multiple comparisons were conducted. Correlation analyses were used to investigate relationships between precipitation and soil water content and salt content. The statistically

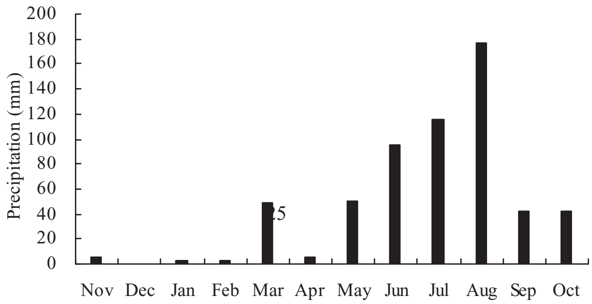

Fig. 1. Precipitation of different months from November 2007 to October 2008.

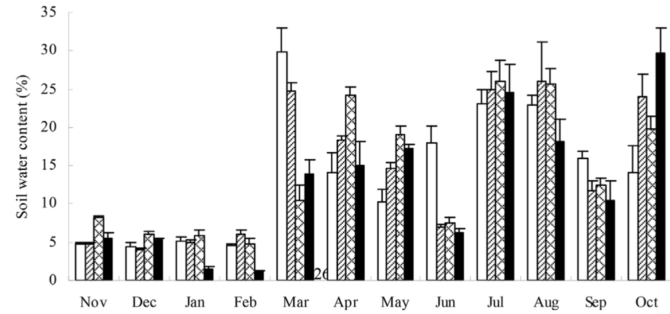

Fig. 2. The dynamic changes of soil water content (%) of *Robinia pseudoacacia* forest.

Table 1
Correlation analysis on precipitation and soil water content in the same time.

	Precipitation	0–20 cm	20–40 cm	40–60 cm	60–80 cm
Precipitation	1	0.701[*]	0.620[*]	0.593[*]	0.496[a]
0–20 cm	0.701[*]	1	0.816[**]	0.522[a]	0.567[a]
20–40 cm	0.620[*]	0.816[**]	1	0.818[**]	0.871[**]
40–60 cm	0.593[*]	0.522[a]	0.818[**]	1	0.842[**]
60–80 cm	0.496[a]	0.567[a]	0.871[**]	0.842[**]	1

[*] Significant at the <0.05 probability levels.
[**] Significant at the <0.01 probability levels.
[a] NS—non-significant at $p < 0.05$.

significant level was set at $P < 0.05$. All statistics were conducted with SPSS for Windows 13.0 (SPSS, Chicago, IL, USA).

3. Results

3.1. Precipitation in study area

The total precipitation in study area was 587.8 mm from November 2007 to October 2008. From March to August (except April), the precipitation increased gradually, reaching the maximum in August, and then decreased (Fig. 1). Nearly 66% of the precipitation fell between June and August. Almost no precipitation occurred from November 2007 to April 2008 (except March). Consequently, drought in the spring (January–April) and main rainfall in the summer (June–August) were the marked rainfall characteristics in the study area.

3.2. Soil water content of the R. pseudoacacia forest

Soil depth showed significant effects on soil water content ($F = 7.74$, $P < 0.01$). Water content in the 0–20 cm soil layer was similar to that in 20–40 cm and 40–60 cm soil layer ($P > 0.05$), and they were significantly higher than in 60–80 cm soil layer ($P < 0.01$). Precipitation was significantly related with the water content in the 0–20 cm, 20–40 cm and 40–60 cm soil layer, and showed no significant correlation with the water content in the 60–80 cm soil layer (Table 1). Therefore, the soil depth of precipitation could effects water content at no more than 60 cm of soil depth. There were significant differences in soil water content among each month. Soil water content in November, December, January and February were low and showed no significant differences among them ($P > 0.05$). Starting from March soil water content increased, reaching the maximum in July and August, and then declined in September and October (Fig. 2). The interaction between soil depth and month was significant ($F = 17.38$, $P < 0.01$). The maximum soil water content was in March for the 0–20 cm soil layer, and in July and August for in the 20–40 cm and 40–60 cm and in October for the 60–80 cm.

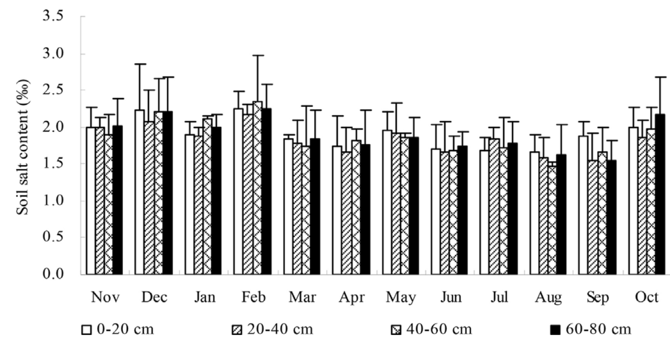

Fig. 3. The dynamic changes of soil salt content (%) of *Robinia pseudoacacia* forest.

Table 2
Correlation analysis on precipitation and soil salt content in the same time.

	Precipitation	0–20 cm	20–40 cm	40–60 cm	60–80 cm
Precipitation	1	−0.70[*]	−0.56[a]	−0.78[**]	−0.61[*]
0–20 cm	−0.70[*]	1	0.84[**]	0.87[**]	0.83[**]
20–40 cm	−0.56[a]	0.84[**]	1	0.87[**]	0.91[**]
40–60 cm	−0.78[**]	0.87[**]	0.87[**]	1	0.91[**]
60–80 cm	−0.61[*]	0.83[**]	0.91[**]	0.91[**]	1

[*] Significant at the <0.05 probability levels.
[**] Significant at the <0.01 probability levels.
[a] NS—non-significant at $p < 0.05$.

3.3. Soil salt content of the R. pseudoacacia forest

No significant differences were shown on soil salt content among different soil layers ($F = 0.36$, $P = 0.78$). However, the month had significant effects on soil salt content ($F = 4.73$, $P < 0.01$). Soil salt content increased gradually from November to February, decreased from February to September and then increased in October (Fig. 3). The interaction between soil depth and month was not significant on soil salt content ($F = 0.19$, $P = 0.99$). Precipitation was strongly and negatively correlated with soil salt content in different soil layers (except 20–40 cm, Table 2), which indicated precipitation was one of the main determinants on soil salt distribution. Furthermore, soil salt content in the 60–80 cm was significantly and positively related to the soil salt content in 0–20 cm, in 20–40 cm and in 40–60 cm (Table 2), which suggested salt in deep soil layer determined surface soil salt content.

3.4. Soil enzyme activity at different seasons

There were significant effects on the activities of soil enzymes examined (except catalase) among the different monthes (Table 3). With the increase of the month, the activity of polyphenol oxidase increased at first and then decreased, and the maximum values appeared at June ($P < 0.01$). The activities of alkaline phosphatase, invertase, protease and urease increased with the month

Table 3
Two-way ANOVA analyses of effects of season and soil depth and their interaction on soil enzyme activity of *Robinia pseudoacacia* forest.

	Season		Soil depth		Season × Soil depth	
Enzyme	F value	P value	F value	P value	F value	P value
Polyphenol oxidase	195.56	<0.01	2.85	0.11	3.52	<0.05
Catalase	1.32	0.30	1.60	0.70	0.07	0.98
Alkaline phosphatase	159.19	<0.01	62.03	<0.01	9.42	<0.01
Invertase	94.96	<0.01	136.28	<0.01	5.12	<0.05
Protease	9.87	<0.01	5.43	<0.05	2.56	0.09
Urease	386.78	<0.01	306.75	<0.01	80.86	<0.01

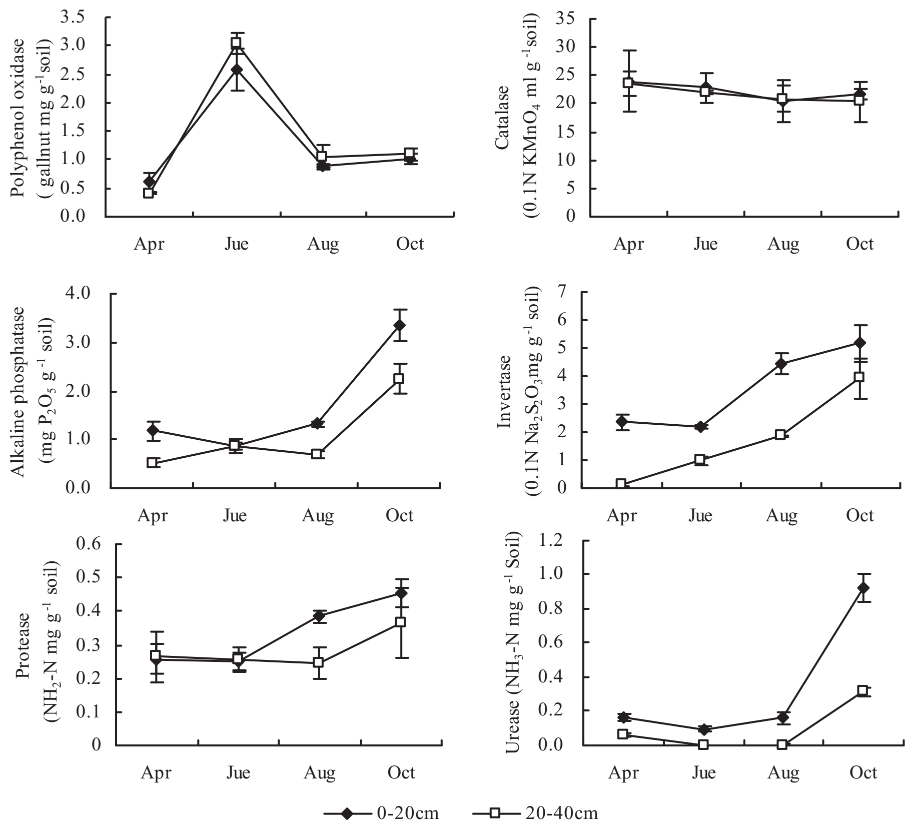

Fig. 4. The soil enzyme activities at different seasons of different soil layers.

Table 4
Two-way ANOVA analyses of effects of season and soil depth and their interaction on soil nutrient of *Robinia pseudoacacia* forest.

	Season		Soil depth		Season × Soil depth	
Soil nutrient	F value	P value	F value	P value	F value	P value
Soil organic matter	66.37	<0.01	91.30	<0.01	6.38	<0.01
Hydrolysis nitrogen	220.24	<0.01	919.50	<0.01	84.81	<0.01
Available potassium	5.30	<0.05	41.20	<0.01	0.94	0.44
Available phosphorus	1252.11	<0.01	1.12	0.35	6.68	<0.01

(Fig. 4). Soil depth didn't show significant effects on the activities of polyphenol oxidase and catalase, whereas it had significant effects on the other soil enzymes (Table 3). The activities of acid phosphatase, invertase, protease and urease were higher in the 0–20 cm than in the 20–40 cm soil layer.

3.5. *Soil nutrients in different seasons*

Month showed significant effects on all soil nutrient indexes (Table 4). As month increased, soil organic matter, hydrolysis nitrogen and available potassium increased obviously (Fig. 5). Available phosphorus increased at first and then decreased, and reached the maximum values at August ($P < 0.01$). Soil hydrolysis nitrogen and available potassium showed significant differences between soil layers (Table 4), and they had higher values in the 0–20 cm than in the 20–40 cm soil layer. However, there were no significant effects of soil depth on available phosphorus.

4. Discussion

Studying the dynamic process of water and salinity change is crucial to the understanding of vegetation distribution and growth in the wetlands (Glaeser et al., 2016; Lin et al., 2016). Soil water content influences both the nutrient uptake by the plants as well as biotic and abiotic processes in the soil (Tullus et al., 2010; Mettrop et al., 2015; Edwards, 2015). In this paper, we discovered that precipitation had significant effects on soil water content, which agreed with the finding from Al-Taai et al. (2014) and Lay et al. (2008). Soil salinity also is one of the important determining factors on plant growth in the coastal region (Dunton et al., 2001; Yan et al., 2016). With the increase of precipitation, we found soil salt content decreased in this paper. Dunton et al. (2001) and Lin et al. (2016) also found the similar results in an estuarine marsh. Moreover,

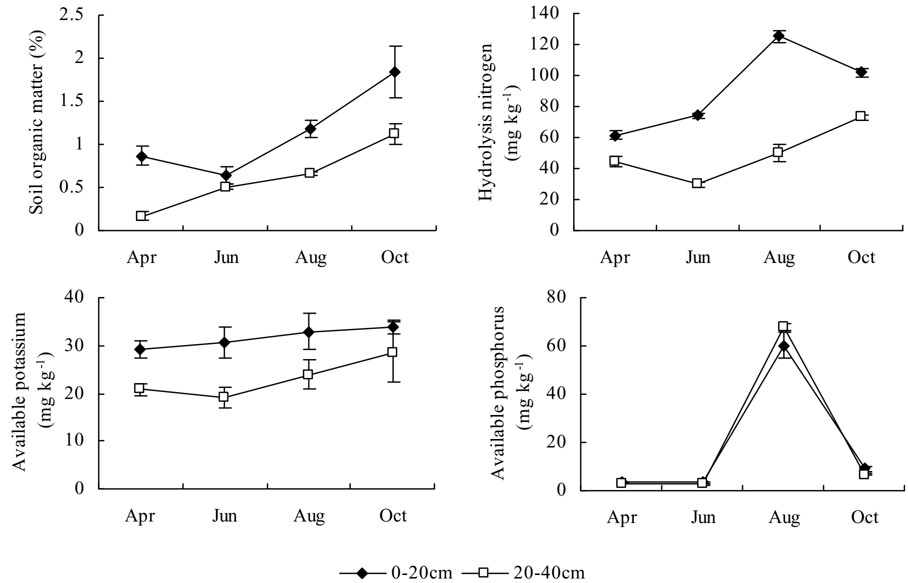

Fig. 5. The soil nutrients at different seasons of different soil layers.

Dunton et al. (2001) thought precipitation events in arid environments may be considered a major physical disturbance that can result in large changes in vegetation composition over a relatively short period (Dunton et al., 2001). In this study area, precipitation season from April to October was consistent with the growth of *R. pseudoacacia* forest. Therefore, precipitation was one of the critical factors of *R. pseudoacacia* forest growth in the Yellow River Delta region.

Soil enzyme activities integrate information both about microbial status and soil physico-chemical conditions (Aon and Colaneri, 2001). Many soil factors (e.g. temperature and soil moisture levels) could change correspondent with seasons, which affect microbial metabolism and production of soil enzymes (Kang and Freeman, 1999). The increase of soil moisture (Baldrian et al., 2013; ÁBear et al., 2014) and temperature (Kang and Freeman, 1999; Fenner et al., 2005; ÁBear et al., 2014) enhances soil enzyme activities. Therefore, the significant increase of polyphenol oxidase activity from April to June was related to the increase of soil water content and temperature. However, the activities of alkaline phosphatase, invertase, protease and urease didn't rise significantly during the same time. ÁBear et al. (2014) thought elevated temperature alone couldn't compensate for the negative effect of drying. Moreover, soil salt content that inhibits soil enzyme activities (Saviozzi et al., 2011; Pan et al., 2013) was higher during this time, too. Hence, soil drought and salinity perhaps were the important limiting factors on soil enzyme activities. Polyphenol oxidase activity dropped abruptly in August, which was related to low oxygen diffusion into soil because of the high precipitation in this month (Kang and Freeman, 1999). Soil hydrolytic enzyme activities (alkaline phosphatase, invertase, protease and urease) increased in August, whereas their maximum values appeared in October. Niu et al. (2012) found rhizosphere ventilation could improve the soil enzyme activity of the potted tomato. The decrease of polyphenol oxidase activity would allow phenolic compounds to accumulate. Phenolics could inhibit the activity of other hydrolase enzymes which are not oxygen limited (Freeman et al., 2001). Consequently, the increase of hydrolytic enzyme activities in October was due to the decrease of soil water content. The hydrolase enzyme activities in this study decreased with depth, which was coincide with Luo et al. (1998) and Bell and Henry (2011). Luo et al. (1998) thought the decrease was related with the decrease of microbial community size.

The changes of soil nutrients are strongly related with plants and abiotic environments (Ladwig et al., 2015). Following the onset of rainfall season, *R. pseudoacacia* grew rapidly. A lot of labile compounds would be exuded through roots and residue of plants (Geisseler et al., 2011), which led to the increase of soil organic matter (Ladwig et al., 2015). Therefore, the increase of soil organic matter in this paper was correlated with the growth of *R. pseudoacacia*. Moreover, plants play an important role on soil microbial community (Chen et al., 2015; Liang et al., 2015). These labile compounds from plants could stimulate soil microbial and enzyme activity (Duan et al., 2015; Xiao et al., 2015). Likewise, increases in soil enzyme activities accelerated the decomposition of organic matter. We also found hydrolytic enzyme, organic matter content and hydrolysis nitrogen increased synchronously. Long droughts can trap nutrients in soil organic matter or on carbonate (Ippolito et al., 2010). However, precipitation could increase nutrient availability in the soil due to high soil water content (Yahdjian and Sala, 2010). Consequently, the increase of soil water content was another reason for the increase of hydrolysis nitrogen, available potassium and available phosphorus. The decrease of available phosphorus in October was perhaps related to the decrease of root growth of *R. pseudoacacia* or the limitation of the accumulated phenolics. In this paper, soil nutrient decreased with the increase of soil depth. High nutrient availability made fine roots concentrate in the soil surface layer (Ugawa et al., 2010), which would impact enzyme activities and microorganism distribution pattern in the soil.

Precipitation is a determining factor on the dynamic process of soil water and salt in the Yellow River Delta. The precipitation induced change on soil drought, salinity and waterlogging showed significant effects on *R. pseudoacacia* growth, soil microbial community size and soil enzyme activities. The impact of precipitation on *R. pseudoacacia* growth, soil microbial community size and soil enzyme activities might be a critical mechanism on clarifying the productivity decline of *R. pseudoacacia* forest in the coastal saline-alkali soil of this region. However, according to the meteorological forecast of the global climate, the annual precipitation pattern will change. Consequently, we need to pay more attention to the change of precipitation pattern and adopt indispensable measures of water conservancy and stand regeneration in order to ensure the sustainable ecological function of *R. pseudoacacia* forest in the Yellow River Delta.

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