Relationship between soil enzyme activity characteristics and plant diversity in different vegetation communities in typical desert areas

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Abstract

For the investigation of the distribution characteristics of soil enzyme activities (SEA) of distinct plant communities (PCs) and the relationship with biodiversity of distinct PCs, the study was carried out on five typical PCs, namely *Calligonum mongolicum*, *Nitraria tangutorum*, *Reaumuria songarica, Calligonum mongolicum*, *Haloxylon ammodendron*, *etc.*, in the desert area of Minqin Liangucheng, Gansu Province, China. SEA and biodiversity were measured at three soil levels: 0–10 cm, 10–20 cm, and 20–30 cm, respectively, and the spatial variations of SEA, the indices of the four biodiversity in different PCs, and the correlation between them were investigated. The findings of the study are as follows: (1) The SEA of the five PCs differed considerably. The activities of sucrase, amylase, urease, alkaline phosphatase, and catalase in the *Reaumuria songarica* community were higher than the other four communities. The *Calligonum mongolicum* community had the highest cellulase activity. The activities of urease, amylase, and cellulase in 0–30 cm depth soil of each PC exhibited a reducing trend with the rise of soil depth, while sucrase and alkaline phosphatase exhibited a rising and subsequently reducing trend with the rise of soil depth in *Reaumuria songarica* community. (2) Plant diversity indices varied among PCs. In the shrub layer and herb layer, the *Reaumuria songarica* community had the highest Margalef richness index and Simpson diversity index, 0.85, 0.49, 0.74, and 0.53, respectively. In the shrub layer, the Shannon-Wiener index was greatest in *Reaumuria songarica* community,0.71. *Calligonum mongolicum* community had the highest Shannon-Wiener index in the herbaceous layer,0.79. *Ephedra przewalskii* community had the largest Pielou index in the herbaceous and shrub layers, 1.00 and 0.61 respectively. (3) SEA is correlated with plant diversity.Soil urease activity was correlated with community diversity and was poorly correlated with plant aboveground biomass. Soil urease activity had a good correlation with the Patrick index in the herb layer and the Margalef index, and the Patrick index in the shrub layer. Alkaline phosphatase activity correlated well with the Pielou index, Patrick index in the herb layer and Patrick index, Shannon-Wiener index, and plant aboveground biomass in the shrub layer. Catalase activity correlated well with the Patrick index and Margalef index in the shrub layer. Soil amylase correlates well with Patrick richness index in the shrub layer, and soil sucrase correlates well with Patrick richness index and Margalef richness index in the herbaceous layer of the plant.In summary, within the desert PCs, the SEA of the *Reaumuria songarica* community were significantly higher than those of the other PCs; the *Reaumuria songarica* community had the highest plant diversity indices in the shrub and herb layers, followed by the *Calligonum mongolicum* and *Ephedra przewalskii* communities; the diversity indices of the shrub and herb layers had a significant relationship with the SEA, especially soil urease, soil alkaline phosphatase, soil catalase, soil amylase and soil sucrase,which acted together to influence the soil microenvironments of the desert plant communities.

1. Introduction

Plants and soil interact as a whole. Plant diversity (PD) is an important indicator of vegetation health and community function. It represents the richness and homogeneity of species in the community, in addition to the interrelationship between distinct natural geographic environments and the community, and can be used as a species diversity to quantitatively characterize the community and ecosystem(Chen Lingzhi,1995). PD directly affects soil enzyme activities (SEA) through plant litter and root secretions. He Jinsheng et al(He Jinsheng and Chen Weilie,1997)found that terrestrial plant species diversity decreased with increasing latitude. Further studies showed that PD in forest ecosystems showed a positive correlation with the activities of soil enzymes including convertase, alkaline phosphatase, and catalase(Yang Wanqin et al,2001). Krämer and Green(Krmer S and Green D M)investigated the correlation between soil phosphatase activities and plants in the subsoil of semi-arid forests and found that SEA were also substantially impacted by the microclimate of the forest floor soil. It is crucial to determine the degree of correlation between PD and SEA and to reveal the relationship between PD and SEA for the protection and restoration of degraded ecosystems in the Minqin desert area.

The specificity of the soil ecology makes the sources of enzymes in it diverse. The most important source of enzymes is the metabolism of various microorganisms in the soil, and a large portion comes from the secretion of plant roots(Liu Shanjiang et al,2011). Soil enzymes are a class of macromolecular proteins that catalyze soil biochemical reactions(Xu Xin-xin et al,2018). Its content is low, but it is substantially implicated in biochemical reactions, which are closely linked to environmental factors including plant growth and the physical and chemical properties of soil. It is one of the key indicators to characterize alterations in the state of soil ecosystems(Gen-ga Yang-pi et al,2022). One of the most prevalent enzymes in the soil is catalase. It is an important redox enzyme system for synthesizing soil humus and preventing biotoxicity by hydrogen peroxide. Measuring the activity of catalase in the soil can visualize the soil organic matter(Zhang H X et al,2018). Wenwen (Ma Wenwen et al,2014) et al. studied soil enzymes of two plant communities (PCs) in the desert grassland of Jinchuan District, Gansu, and found that *Kalidium foliatum* had higher sucrase, urease, phosphatase, and catalase activities than *Alhagi camelorum*. Wenshan(Shao Wenshan et al,2016)et al.'s study on soil enzymes of distinct PCs in the Shabianzi area of Ningxia concluded that *Neotrinia splendens* and *Artemisia ordosica* had higher urease activities in the topsoil, while *Sophora alopecuroides* and *Neotrinia splendens* had higher soil phosphatase activity. The study of soil enzymes of typical PCs at the eastern edge of the Maowusu Sandland by Wang(Wang Jia-wei,2018)showed that vegetative SEA were *Caragana korshinskii* > *Salix cheilophila* > *Medicago sativa* > *Sophora alopecuroides*, and the differences were significant. Different plants are adapted to different soil environments and have significant differences in biomass, which leads to differences in the degradation of apoplastic material and the activity of enzymes secreted between roots(Li Jing et al,2013).

In this study, the soils of *Nitraria tangutorum*, *Reaumuria songarica*, *Calligonum mongolicum*, *Haloxylon ammodendron*, and *Calligonum mongolicum*, which are typical PCs in Minqin Liangucheng National Nature Reserve, were used. The changes in SEA at distinct depths were characterized by vertical distribution and changes in PD indices of distinct PCs. The differences in SEA of different PCs and the PD index of distinct PCs were compared. Based on vertical changes in SEA, correlation analysis and redundancy analysis were employed to discover the intrinsic relationship between SEA, and to theoretically understand the pattern of change of SEA and the influencing factors in the Minqin Desert Area. This will further deepen the understanding of the material cycling process of the soil in the Minqin desert area, and provide some theoretical basic information for discovering the recovery of vegetation, land improvement, and scientific management in the desert area.

2. Material and Method

2.1 Overview of the Pilot Zone

Minqin County is situated in the northeastern part of the Hexi Corridor, downstream of the Shiyang River Basin, bordering Liangzhou District in the south, connected with Jinchang City in the southwest and bordered by the two major deserts of Badanjilin and Tengger in the east, west, and north. The lowest altitude in the territory is 1298 meters, the highest altitude is 1936 meters, and the average altitude is 1400 meters. It consists of three basic landforms: desert, low hills, and plains. Low hills, plains, deserts, Gobi, and other interlaced distribution of the territory, is a sensitive area of climate change and fragile ecological environment. Minqin is a temperate continental arid climate zone with four different seasons. Windy winter and spring, hot summer, temperature daily and yearly changes; less precipitation, uneven distribution; evaporation, dry climate, high frequency of drought. The average temperature for many years is 8.8℃, the extreme minimum temperature is 29.5℃, and the extreme maximum temperature is 41.7℃. The average annual difference in temperature is 31.8℃, and the average daily difference in temperature is 14.3℃. Among them is Minqin Liangucheng National Nature Reserve (102°30'~103°57'E, 38°10'~39°9'N). Minqin Liangucheng National Nature Reserve is a desert ecological type nature reserve, which is the only national nature reserve of desert type ecosystem in Gansu Province, with a total land area of 3898.8 Km^2. Due to the strong solar radiation, abundant light, high evaporation, and dry climate, the common PCs in the reserve include *Ephedra przewalskii*, *Reaumuria songarica*, *Nitraria tangutorum*, *Calligonum mongolicum*, *Haloxylon ammodendron*, *Kalidium foliatum*, *Zygophyllum xanthoxylum (Bunge) Maxim*, *Potaninia mongolica* and other plants. They are substantially implicated in the reserve’s normal ecological functioning(LI Weilong et al,2011).

There is less artificial interference in the reserve. The local desert vegetation communities are distinctly zonal. The natural vegetation is dominated by arid, sandy, and saline perennial herbs, shrubs, and semi-shrubs. The natural vegetation communities are Community of *Nitraria tangutorum*, Community of *Oxytropis aciphylla*, Community of *Kalidium foliatum*, Community of *Calligonum mongolicum*, Community of *Potaninia mongolica*, Community of *Zygophyllum xanthoxylon*, Community of *Calligonum mongolicum*, Community of *Tamarix chinensis*, Community of *Reaumuria songarica*, and so on. The protected area is relatively rich in plant and animal resources, complex composition of zones, and fragile ecosystems, and is an important research base for studying desert ecological environment. At the same time, the protection and management of the ecological setting of the protected region are invaluable for research and offering reference value for similar areas, both domestically and internationally(Ma Jing et al,2019).

2.2 Sample Plot Selection and Experimental Methods

Within the Minqin Liangucheng National Nature Reserve, representative and normal-growing *Ephedra przewalskii*, *Reaumuria songarica*, *Nitraria tangutorum*, *Calligonum mongolicum*, and *Haloxylon ammodendron* species were selected to be distributed in different areas. Five large sample plots were selected in the more widely distributed *Reaumuria songarica*, *Nitraria tangutorum*, and *Haloxylon ammodendron* communities, respectively. Three large sample plots were chosen in each of the less distributed *Ephedra przewalskii* and *Calligonum mongolicum* communities. The 21 large sample plots in total were selected for this research. Three 10 m×10 m sample plots were set up uniformly in the area with a relatively homogeneous distribution of vegetation and soil in each large sample plot, and 63 sample plots in total were set up. Each sample plot contained five sampling points in accordance with the "S" shape sampling technique.

Spots were distributed in an "S" pattern within each sample plot to remove surface litter. In layers of 0–10 cm (surface layer), 10–20 cm (middle layer), and 20–30 cm (deep layer), soil samples were collected using a conventional soil auger. After removing stones, plant and animal debris, and other debris from the soil, the samples from the same layer were mixed homogeneously and transported back to the laboratory in a self-sealing bag under low-temperature refrigeration. For indoor tests, the soil samples were air-dried, ground, and sieved (2 mm) for the determination and calculation of soil enzymes and PD indices. The PC questionnaire is shown in Table 1.

Table 1

Plant community questionnaire

Community Type	Coverage	Primary Plant Types
Ephedra przewalskii	30%-35%	*Ephedra przewalskii, Nitraria sphaerocarpa, Nitraria roborowskii*
Reaumuria songarica	35%-45%	*Reaumuria songarica, Ceratoides compacta, Nitraria sphaerocarpa, Nitraria roborowskii*
Nitraria tangutorum	35%-50%	*Nitraria roborowskii, Desert Stipa capillata, Caragana Korshinkii kom, Reaumuria songarica, Artificial Haloxylon ammodendron*
Calligonum mongolicum	40%-45%	*Calligonum mongolicum, Calligonum mongolicum, Artemisia frigida*
Artificial Haloxylon ammodendron	35%-50%	*Artificial Haloxylon ammodendron, Nitraria roborowskii, Reaumuria songarica*

2.3 Research Methods

2.3.1 Determination of Soil Enzyme Activity

For the determination of sucrase, amylase, urease, alkaline phosphatase, catalase and cellulase, refer to *Soil Enzymes and Their Research Methods* by Songyin Guan(Songyin Guan,1986).

2.3.2 Calculation of Plant Diversity Index

The species diversity of the shrub layer and herb layer within each PC sample plot was calculated separately based on the sample plot data detected in the field. The indices used to measure diversity in this study included the species richness index Patrick index (*R*), Margalef index (*dMa*), Simpson index (*D*), Shannon-Wiener index (*H*), and Pielou index (*Jws*)(Ma K P et al,1995).

2.3.3 Data Processing and Analysis

The data was organized and analyzed employing SPSS 20.0 and Microsoft Excel 2013. Employing the two-way analysis of variance (ANOVA), the SEA of the five plant species in different soil depths were contrasted. The correlation between SEA and PD index was analyzed by Pearson correlation analysis using Canoco 5.0 for graphing.

3. Result and Analysis

3.1Changes in soil enzyme activities in different plant communities

As shown in Figure 1 (a), comparing soil sucrase activity at different soil levels, it was found that soil sucrase activity of the *Reaumuria songarica* community and *Calligonum mongolicum* community showed an increase and then a decrease in the vertical profile. *Reaumuria songarica* community soil sucrase activity was 10-20 cm > 20-30 cm > 0-10 cm, while *Calligonum mongolicum* community soil sucrase activity was 10-20 cm > 0-10 cm > 20-30 cm. Soil sucrase activity was reduced with rising soil depth in the vertical profile of the other three PCs.

As depicted in Figure (b), soil amylase activity of all five PCs showed 0-10 cm > 10-20 cm > 20-30 cm among different soil levels. The difference between 0-10 cm and 10-20 cm soil amylase activity of *Ephedra przewalskii*, *Reaumuria songarica*, *Calligonum mongolicum*, and *Artificial Haloxylon ammodendron* communities was small. The difference in soil amylase activity between 10-20 cm and 20-30 cm was larger in the *Nitraria tangutorum* community.

As depicted in Figure (c), the activity of soil cellulase of all five PCs gradually reduced with rising soil depth, but the difference in soil cellulase activity between different depths was not significant. *Ephedra przewalskii*, *Calligonum mongolicum*, and *Artificial Haloxylon ammodendron* communities had significant differences in soil cellulase activity between 0-10 cm, 10-20 cm, and 20-30 cm. *Reaumuria songarica* and *Nitraria tangutorum* communities differed significantly in 10-20 cm and 20-30 cm soil cellulase activity.

As depicted in Figure (d), soil urease activity of all five PCs reduced gradually with increasing soil depth. *Ephedra przewalskii* community and *Calligonum mongolicum* community had significantly higher soil urease activity from 0-10 cm than their 10-20 cm and 20-30 cm soil urease activity. *Reaumuria songarica* community, *Nitraria tangutorum* community, and *Artificial Haloxylon ammodendron* community also had the highest 0-10 cm soil urease activity, but the difference with 10-20 cm and 20-30 cm soil was not substantial.

As can be seen in Figure (e), the soil was vertically profiled. Except for the *Reaumuria songarica* community where the size of alkaline phosphatase activity was 10-20 cm > 0-10 cm > 20-30 cm, soil alkaline phosphatase activity of all the other four PC types decreased gradually with increasing soil depth. Soil alkaline phosphatase activity of *Calligonum mongolicum* community 10-20 cm and 20-30 cm varied substantially from that of 0-10 cm soil, and there was no substantial distinction in soil alkaline phosphatase activity among distinct soil depths of the other four PC types.

As depicted in Figure (f), soil catalase activity of *Reaumuria songarica* and *Nitraria tangutorum* communities gradually increased with soil depth in different soil levels, while soil peroxidase activity of *Calligonum mongolicum* community decreased with soil depth, and 0-10 cm and 10-20 cm and 0-10 cm were different from each other. 10 cm was substantially distinct from 10-20 cm and 20-30 cm soil. Soil catalase activity in the *Ephedra przewalskii* community was 0-10 cm > 20-30 cm > 10-20 cm, while *Artificial Haloxylon ammodendron* was 20-30 cm > 0-10 cm > 10-20 cm. The differences in soil alkaline phosphatase activity were not significant.

3.2 Analysis of plant factor indices of different plant communities

Based on the Margalef richness indices of different PCs, Figure 2 (a) illustrates that the richness indices of the shrub layer and herb layer of each community were highest for the *Reaumuria songarica* community. The Margalef index of the shrub layer and herb layer were 0.853 and 0.740 respectively. *Ephedra przewalskii* herb layer had the lowest Margalef index of 0.187. The shrub layer of *Calligonum mongolicum* had the lowest Margalef index of 0.126. The Margalef richness index of the herb layer of each community was in the order of *Reaumuria songarica* community > *Artificial Haloxylon ammodendron* community > *Nitraria tangutorum* community > *Calligonum mongolicum* community > *Ephedra przewalskii* Community. The magnitude of the Margalef richness index in the shrub layer of each community was *Reaumuria songarica* community > *Nitraria tangutorum* community > *Artificial Haloxylon ammodendron* community > *Ephedra przewalskii* community > *Calligonum mongolicum* community.

The variation of the Simpson diversity index in different PCs is depicted in Figure (b). It is evident that *Reaumuria songarica* community has the highest Simpson index in the herbaceous layer and shrub layer, which were 0.494 and 0.528, respectively, and the lowest Simpson index was found in the herbaceous layer of the *Ephedra przewalskii* community (0.012). The lowest Simpson index was found in the shrub layer of the *Calligonum mongolicum* community (0.089). The order of Simpson's diversity index in the herb layer of each community was *Reaumuria songarica* community > *Calligonum mongolicum* community > *Artificial Haloxylon ammodendron* community > *Nitraria tangutorum* community > *Ephedra przewalskii* community. The size of Simpson's diversity index in the shrub layer of each community was

Reaumuria songarica community > *Nitraria tangutorum* community > *Haloxylon ammodendron* community > *Ephedra przewalskii* community > *Calligonum mongolicum* community.

The variation of the Shannon-Wiener diversity index of different PCs is depicted in Figure (c). It is evident that in the herbaceous layer, the *Calligonum mongolicum* community had the highest Shannon-Wiener index of 0.787; the *Ephedra przewalskii* community had the lowest of 0.214. In the shrub layer, the *Reaumuria songarica* community had the highest of 0.713 and the lowest at 0.288 for *Haloxylon ammodendron*. In the herbaceous layer of each community, the magnitude of Shannon-Wiener diversity indices was *Calligonum mongolicum* > *Reaumuria songarica* > *Nitraria tangutorum*. tangutorum Bobrov > Haloxylon ammodendron > *Ephedra przewalskii*. The magnitude of the Shannon-Wiener diversity index in the shrub layer of each community was *Reaumuria songarica* > *Ephedra przewalskii* > *Nitraria tangutorum* > *Calligonum mongolicum* > Haloxylon ammodendron.

The variation of the Pielou evenness index of different PCs can be seen according to Figure (d). *Ephedra przewalskii* community had the largest Pielou index in both herbaceous and shrub layers with 0.998 and 0.483 respectively. *Haloxylon ammodendron* community had the lowest Pielou index in the herbaceous layer with 0.445. *Nitraria tangutorum* community had the lowest Pielou index in the herbaceous layer with 0.445. The *Nitraria tangutorum* community had the lowest Pielou index in the shrub layer with 0.299. The size of the Pielou evenness index in the herb layer of each PC was in the order of *Ephedra przewalskii* community > *Calligonum mongolicum* community > *Nitraria tangutorum* > *Reaumuria songarica* > Haloxylon ammodendron. The size of Pielou's evenness index in the shrub layer of each PC was in the order of *Ephedra przewalskii* community > *Reaumuria songarica* community > *Calligonum mongolicum* community > *Haloxylon ammodendron* community > *Nitraria tangutorum* community.

3.4 Relationship between soil enzyme activities and biodiversity

Calculation of Pearson correlation coefficients between SEA and biodiversity demonstrated that the correlation between the diversity index of each PC, vegetation cover, and biomass of the aboveground parts and soil enzymes was more general, and there were differences in the correlation between the activities of distinct types of soil enzymes and the factors of plants. There were also differences between soil layers at different depths.

The correlation coefficients between SEA and biodiversity in the 0-10 cm soil layer are shown in Figure 3(a). Soil urease activity was significantly and positively correlated with the Patrick richness index in the phytochemical layer (P<0.05) and exhibited a substantial positive correlation with the Margalef richness index in the herbaceous layer (P<0.05). Soil alkaline phosphatase showed a negative correlation (P<0.05) with the Pielou evenness index and plant aboveground biomass in the herbaceous layer and a substantial positive correlation (P<0.05) with Patrick richness index and Shannon-Wiener index in the shrub layer.

The correlation coefficients between SEA and biodiversity in the 10-20 cm depth soil layer are shown in Figure (b). Soil urease activity had a substantial positive correlation ($P<0.001$) with the Patrick richness index of the biodiversity herb layer. Soil alkaline phosphatase activity exhibited a positive correlation ($P<0.05$) with the Patrick richness index and the positive correlation (P<0.01) with Margalef richness index in the herb layer and Patrick richness index in the shrub layer(P<0.01) and a negative correlation ($P<0.05$) with plant aboveground biomass. Soil amylase was positively correlated with Patrick richness index in the herb layer and Patrick richness index in the shrub layer of the plant(P<0.01).

The correlation coefficients between SEA and biodiversity in the 20-30 cm depth soil layer are shown in Figure (c). Soil urease activity had a positive correlation ($P<0.05$) with the Patrick richness index in the plant shrub layer. Soil alkaline phosphatase activity showed a significant positive correlation (P<0.05) with Patrick richness index in the plant herb layer, a positive correlation (P<0.01) with Margalef richness index in the plant herb layer, and Patrick richness index in the plant shrub layer, and a negative correlation (P<0.01) with the plant aboveround biomass.Soil sucrase was positively correlated with Patrick richness index and Margalef richness index in the plant herb layer (P<0.01) and soil amylase was positively correlated with Patrick richness index in the shrub layer of plants (P<0.01).

4. Discussion

4.1 Relationship between soil enzyme activities in different plant communities

Soil enzymes are biocatalysts in soil, which are involved in the process of soil genesis and development as well as soil fertility formation, and are substantially implicated in the material cycle of the ecosystem in the Minqin desert area. It can reveal the direction and intensity of biochemical processes in soil(Liu C et al,2007; Zhu Haiqiang et al,2017). Sucrase and urease are important hydrolytic enzymes in soil. Sucrase is able to catalyze the hydrolysis of a wide range of oligosaccharides and is significant in the soil carbon cycle. In this study, the soil sucrase activity of the *Reaumuria songarica* community was substantially greater contrasted to that of the other four PCs. The soil urease activity of the *Reaumuria songarica* community was also greater contrasted to that of the other PCs but the difference was not significant with that of *Ephedra przewalskii* and *Nitraria tangutorum* communities. *Ephedra przewalskii* and *Nitraria tangutorum* communities, but the difference was not significant. Chunyan et al.(Zhu Haiqiang et al,2020)also showed that *Reaumuria songarica* significantly increased soil sucrase activity, but not urease activity, in the eastern foothills of Helan Mountain. Xu et al. concluded that desert plants are able to secrete soil enzymes through inter-root secretion and inter-root microorganisms, and effectively promote soil carbon cycling, which led to a substantial rise in soil sucrase activity; however, desert plants did not have a substantial influence on soil urease activity, perhaps owing to the fact that apoplastic materials of desert plants are relatively scarce and easy to migrate, which could not deliver sufficient organic matter to the soil, and did not have enough nitrogen to support the activity of soil enzymes. The amylase activity of soil from different communities was also shown as *Reaumuria songarica* community

> *Nitraria tangutorum* community > *Ephedra przewalskii* community > *Calligonum mongolicum* community > *Haloxylon ammodendron* community, which was consistent with the sucrase activity. sucrase activity performance. The minimum values of the five enzyme activities were all found in the *Haloxylon ammodendron* community, which was due to the monoculture of *Haloxylon ammodendron* community with less surface vegetation and less litter, and the lower organic matter input capacity of the soil, so the SEA were also lower. Phosphatases are enzymes that promote the decomposition of organophosphorus compounds in the soil, and the level of activity had a direct relation with the bioavailability of organophosphorus in the soi(Shu Shiyan et al,2010). Alkaline phosphatase activity was greater in the *Reaumuria songarica* community, the *Calligonum mongolicum* community, and the *Ephedra przewalskii* community, indicating that microbial nutrient requirements in the soils of these three communities were most severely phosphorus-limited, while it was lower in *Calligonum mongolicum* and *Haloxylon ammodendron* communities, indicating that phosphorus limitation was less severe in the soils of these two communities. Catalase can indicate the intensity of soil oxidative processes and in some sense can reflect the intensity of soil microbiological processe(Lu Ping et al,2002). Soil catalase activity among the five PCs differed less compared to sucrase and urease because catalase is able to catalyze the decomposition of excess plant-harmful hydrogen peroxide in the soil. The region is all desert-type sandy soil that contains different amounts of plant-harmful hydrogen peroxide, so the difference in catalase activity is less.

Numerous studies have revealed that SEA decreases with increasing soil depth (Wu Xu-dong et al,2013; Yang Ning et al,2013; Hu Lei et al,2014). From the vertical distribution of soil layers, soil phosphatase, sucrase and urease activities all decreased with increasing soil depth, which is in agreement with related studies reported(Yu De-liang,2019), but different from the results of Wang Xuelin(Wang X L et al,2021)et al.'s study on soil enzyme activities in sandy camphor pine plantation forests.In the current research, the activities of soil urease, amylase, and cellulase of each PC were maximum in the soil at 0–10 cm depth and reduced with rising soil depth. Sucrase and alkaline phosphatase activities also displayed a reducing trend with rising soil depth, indicating that the activities of these five soil enzymes mainly accumulated in the surface layer. The activities of sucrase and alkaline phosphatase also showed a decreasing trend with soil depth, indicating that these five soil enzymes were mainly accumulated in the surface layer. As the soil surface accumulates more apoplastic matter and humus than the deeper soil, the organic matter content is high, the nutrient source is rich in favor of microbial survival, and the hydrothermal conditions and aeration in the surface layer are good, the microbial growth is vigorous and the metabolism is more active (Gong Huan-huan et al,2017), resulting in large enzyme activities in the surface layer of the soil. In addition, due to the abundant light, strong evaporation, scarce rainfall and dry weather in this area, which is a typical temperate continental climate (Yang LJ et al,2020), if rainfall can only be stored in the surface layer of the soil, as the soil depth deepens, the lower biomass decreases leading to a reduction in soil nutrient sources, and soil fertility conditions and nutrient element levels tend to be unfavorable for microbial growth and reproduction (Wang Wei-dong et al,2015), resulting in a decrease in SEA. The catalase activity showed different characteristics from the other five enzymes in terms of variation with soil depth. Soil catalase activity of the *Reaumuria songarica* community and *Nitraria tangutorum* community increased gradually with soil depth, whereas the soil catalase activity of *Ephedra przewalskii* community and *Haloxylon ammodendron* showed a decrease and then a rise in activity with rising soil depth, while *Calligonum mongolicum* showed a reduction in activity with rising soil depth. According to Linhai(Li Lin-hai et al,2012), catalase is an oxidoreductase, and its activity is not only related to the composition of apoplastic material and root secretion but also to the soil environment and other factors.

4.2 Response of soil enzyme activities to biodiversity in different plant communities

In the study of plant species diversity, a single index cannot adequately reflect the status of community diversity, so most of the related studies have used the ecological dominance, evenness, richness, and diversity indices of plant species to jointly illustrate the species diversity of PCs(Yang Z Q et al,2018). The decomposition of plant apoplastic is accomplished by the synergistic action of enzymes in the apoplastic and soil. Both plant apoplastic degradation and root secretion can input enzymes into the soil and enhance the enzyme activity of the soil (Songyin Guan,1986). The results of this study on the measurement of herbaceous and shrub layers of different PCs showed that Simpson's diversity index and Margalef's richness index were maximum in both shrub and herbaceous layers of the *Reaumuria songarica* community. The Shannon-Wiener index of the *Reaumuria songarica* community in the shrub layer was also the largest. The Margalef index refers to the number of species in the community and also indicates the degree of species richness in the biome; the greater the Simpson index, the smaller the number of dominant species in the community and the higher the degree of singularity; the Shannon-Wiener index uses the number of species to reflect the diversity of community categories; a rise in the number of species in the community indicates a rise in the complexity of the community, and the greater the Shannon-Wiener index is, the more informative the community is. The size of the Pielou evenness index can reflect the degree of evenness of the community, and it is used to estimate the degree of evenness of the dispersal of all the species in the community, and Ephedra evenness index can be used to estimate the degree of evenness of the dispersal of all species in the community. The Pielou index of the *Ephedra przewalskii* community was the largest in both herbaceous and shrub layers.

In the current research on the correlation between soil urease activity and PC diversity at different depths, it was discovered that soil urease activity had a good positive correlation with the Patrick richness index($P < 0.01$) and Margalef richness index $P < 0.05$ in the herb layer at a depth of 0–10 cm. In the study of Li(Li Yuanyuan,2018), soil urease activity was discovered to be a substantial positive correlation with the richness index of the plant shrub layer, and the correlation with the herbaceous layer was not significant. Soil alkaline phosphatase activity was negatively correlated with the Pielou evenness index and plant aboveground biomass in the herb layer $P < 0.05$ and a positive correlation with the Shannon-Wiener index and Patrick richness index in the shrub layer $P < 0.05$. In the 10–20 cm depth soil layer, soil urease activity was also positively correlated with the Patrick richness index $P < 0.01$ in the herb layer. Contrary to Li's study. An Xiaofei et al(An Xiaofei et al,2022)found that soil urease and alkaline phosphatase were one of the main factors affecting woody plant diversity in the region by studying the relationship between plant diversity and soil enzyme activities in sinkhole habitats, which is consistent with the results of this study. In the 20–30 cm depth soil layer, soil urease activity showed a positive correlation with the Patrick richness index in the herbaceous layer, which was the same as 0–10 cm and 10–20 cm soils. In this study, soil alkaline phosphatase was found to exhibit a significant positive correlation ($P < 0.05$) with Patrick richness index in the herbaceous layer of the plant, a positive correlation with Margalef richness index in the herbaceous layer of the plant, and Patrick richness index in the shrub layer of the plant, as well as a negative correlation ($P < 0.01$) with the plant aboveground biomass. The study of Wang Jia(Wang Jia et al,2021) and others also found that Margalef richness index was significantly positively correlated with both phosphatase activity and sucrase activity and highly significant positively correlated with urease activity in the 0–20 cm soil layer, and highly significant positively correlated with urease activity in the 20–40 cm soil layer. Meanwhile, Jiao et al(Jiao Xiaoliang et al) also found that the species richness index and Shannon index of plant communities in reclaimed areas were significantly and positively correlated with soil urease and alkaline phosphatase activities, which was consistent with the results of this study. In this study, soil sucrase was positively correlated ($P < 0.01$) with Patrick richness index and Margalef richness index in the herbaceous layer of the plant.Liao Quanlan et al(Liao Quanlan et al,2021) also showed that the Shannon-Wiener index, Margalef richness index, and Pielou evenness index were positively correlated with sucrase activity. However,Wang Jia et al(Wang Jia et al,2021)found that the number of plant species had a significant positive correlation with soil urease and phosphatase activities, while the Shannon index, Pielou index and Simpson index had a weaker correlation with the activities of these two enzymes through the study of plant diversity and SEA in fallow land,which was different from the results of this paper, which was due to the fact that plant species, apomictic material, and root system varied in different study areas. This study area is an arid desert ecosystem, which is different from the typical arid zone fallow land and karst forest reserve in terms of hydrology, soil, topography, climate and other regional environmental conditions. Plant diversity also varies in its effect on soil enzyme production, thus leading to different results. Therefore, there is a poor correlation between the activities of certain enzymes in soil and plant diversity, the species diversity of plant communities increases with the increase of soil fertility, and the enzyme activities are highly susceptible to the combined effects of spatial heterogeneity, hydrothermal conditions, etc.(TIAN J,2019), and soil enzyme activities in different habitats have different forms of response with the succession of vegetation and the adjustment of the structure of communities(An Xiaofei et al,2022). Therefore, when studying SEA and plant diversity in the future, we should consider more effects of regional environmental conditions such as hydrology, soil, topography, and climate to study the relationship between soil and vegetation more accurately.

5. Conclusion

In the current research, we characterized the alterations of soil catalase, sucrase, urease, amylase, cellulase, and alkaline phosphatase activities in the depths of 0-10 cm, 10-20 cm, and 20-30 cm of five typical PCs in Minqin Liangucheng desert area, and calculated four PD indices in the herbaceous and shrub layers of the five typical PCs in the desert area of Minqin Liangucheng, and analyzed the correlation between the activities of six soil enzymes and biodiversity, and obtained the following conclusions.

(1) The activities of soil urease, amylase, and cellulase in the 0-30 cm depth of each PC exhibited a reducing trend with the rise of soil depth, while sucrase and alkaline phosphatase exhibited a rising and subsequently reducing trend with the rise of depth in *Reaumuria songarica* community.

(2) The PD indices of different PCs varied: Margalef's richness index and Simpson's diversity index were the maximum in the shrub layer and herb layer of the *Reaumuria songarica* community, 0.85, 0.49, 0.74, and 0.53, respectively. Shannon-Wiener index was the maximum in the shrub layer of the *Reaumuria songarica* community,0.71. *Calligonum mongolicum* community had the highest Shannon-Wiener index in the herbaceous layer,0.79. *Ephedra przewalskii* community had the largest Pielou index in the herbaceous and shrub layers, 1.00 and 0.61 respectively.

(3) The correlation between biodiversity and soil urease activity varied at different depths. Overall in the 0-10 cm soil layer, soil urease and soil alkaline phosphatase had a good correlation with each plant factor, in the 10-20 cm soil layer, in addition to soil urease and soil alkaline phosphatase having a good correlation with each plant factor, soil amylase also had a good correlation with each plant factor, and in the 20-30 cm layer, the correlation of each soil enzyme activity with each plant factor was the strongest, especially alkaline phosphatase, followed by soil sucrase, soil amylase and soil urease.

In summary, within the desert-like PCs, the diversity indices of plant shrubs and herbs were more significantly associated with SEAs, especially, soil urease and soil alkaline phosphatase were the largest, followed by soil catalase and sucrase.

Declarations

Funding statement

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Declaration of Competing Interests

The authors of this article have no conflicts of interest.

Data Availability declaration

All data in this article are available.

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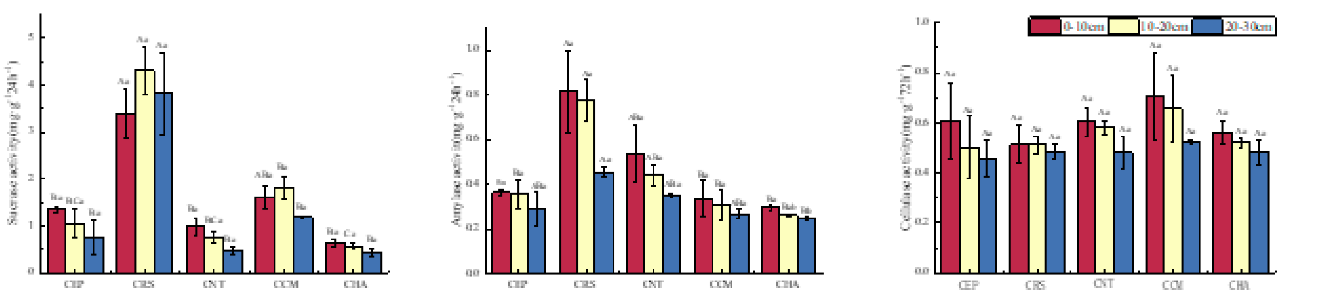
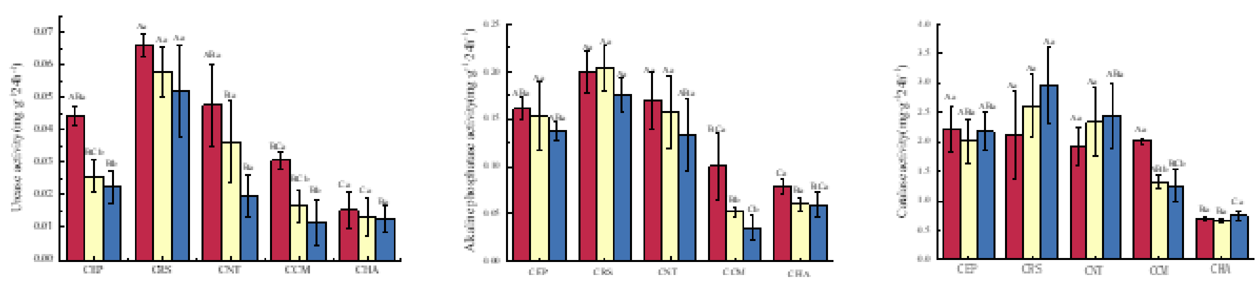
Figures



(a) characterization of soil sucrase activity (b) characterization of soil amylase activity (c) characterization of soil cellulase activity

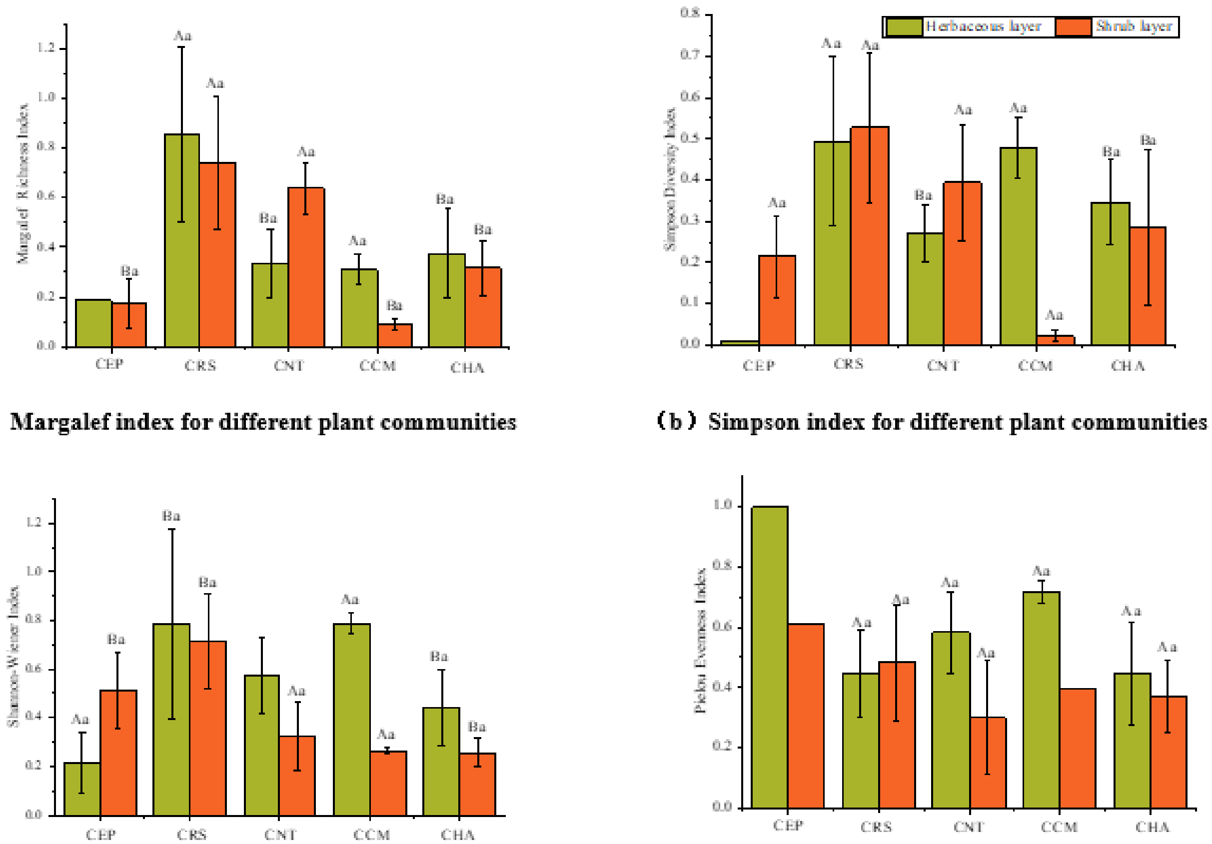


(d) characterization of soil urease activity (e) characterization of soil alkaline phosphatase activity (f) characterization of soil catalase activity

Figure 1

Alterations in soil enzyme activities in different soil layers of different plant communities

Note 1: Upper case letters indicate variability (P<0.05) among distinct PCs in the same soil layer; lower case letters indicate the same plant community among distinct soil layers (P<0.05). The Line segments in the graphs are the mean ± standard deviation of each plant community, the same as below. In the figure, CEP stands for the *Ephedra przewalskii*community, CRS stands for the *Reaumuria songarica*community, CNT stands for the *Nitraria tangutorum*community, CCM stands for the *Calligonum mongolicum* community, and CHA stands for the *Artificial Haloxylon ammodendron*community, the same as below.



（a）Margalef index for different plant communities

（b）Simpson index for different plant communities

（c）Shannon-Wiener index for different plant communities

（d）Pielou index for different plant communities

Figure 2

Diversity index of distinct plant communities

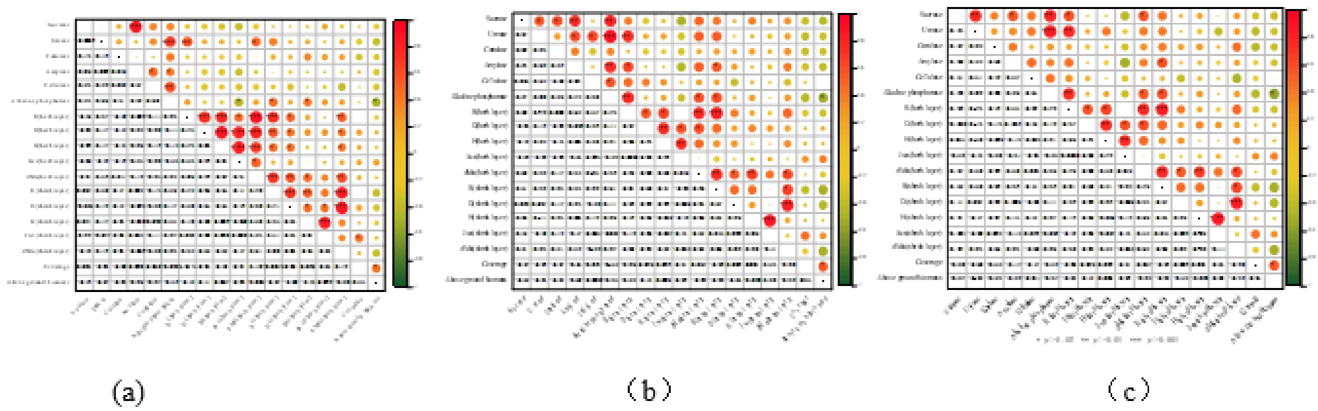


Figure 3

Correlation coefficients between soil enzyme activities and biodiversity in the 0-30 cm soil layer in the Minqin desert area

(a) (b) (c) Correlation coefficients between SEA and biodiversity in 0-10 cm, 10-20 cm, and 20-30 cm soil horizons in the Minqin desert area

Note2: R is the Patrick richness index; D is the Simpson's diversity index; H is the Shannon-Wiener diversity index; Jws is the Pielou evenness index; dMa is the Margalef richness index.