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Relationship and its ecological significance between plant species diversity and ecosystem function of soil conservation in semi-humid evergreen forests, Yunnan Province, China

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Abstract In recent years, the relationship between biodiversity and ecosystem stability, productivity, and other ecosystem functions has been extensively studied by using theoretical approaches, experimental investigations, and observations in natural ecosystems; however, results are controversial. For example, simple systems were more stable than complex systems in theoretical studies, and higher productivity was observed in human-made ecosystems with poorer species composition, etc. The role of biodiversity in the ecosystem, such as its influence on sustainability, stability, and productivity, is still not understood. Because accelerated soil-erosion in various ecosystems has caused a decrease of primary productivity, a logical way used in the study of the relationship between biodiversity and ecosystem function can be used to study the relationship between plant species diversity and soil conservation. In addition, biodiversity is a product of evolutionary history, and soil erosion is a key factor controlling the evolution of modern environment on the surface of the Earth. A study on the relationship between biodiversity and soil-erosion processes could help us understand the environmental evolution of Earth.

Fifteen 10 m × 40 m standard runoff plots were established to measure surface runoff, soil erosion, and total P loss in different secondary communities of semi-humid evergreen broad-leaved forests that varied in composition, diversity, and level of disturbance and soil erosion. The following five communities were studied: AEI (Ass. *Elsholtzia fruticosa* + *Imperata cylindrical*), APMO (Ass. *Pinus yunnanensis* + *Myrsine africana* + *Oplismenus compsitus*), APLO (Ass. *Pinus yunnanensis* + *Lithocarpus confines* + *Oplismenus*

compsitus), AEME (Ass. *Eucalyptus smith* + *Myrsine africana* + *Eupatorium adenophorum*), and ACKV (Ass. *Cyclobalanopsis glaucooides* + *Keteleeria evelyniana* + *Viola duelouxii*). Tree density, the diameter of the tree at breast height, and the hygroscopic volume of plant leaves were determined in each plot.

Results indicated that surface runoff, soil erosion, and total P loss decreased as a power function with increase in plant species diversity. Their average values for three years were 960.20 m³/(hm²·year), 11.4 t/(hm²·year), and 127.69 kg/(hm²·year) in the plot with the lowest species diversity, and 75.55 m³/(hm²·year), 0.28 t/(hm²·year), and 4.71 kg/(hm²·year) in the plot with the highest species diversity, 12, 50, and 25 times respectively lower compared with the lowest species diversity plots. The coefficients of variation of surface runoff, soil erosion, and total P loss also followed a power function with the increase of plant species diversity, and were 287.6, 534.21, and 315.47 respectively in the lowest species diversity plot and 57.93, 187.94, and 59.2 in the highest species diversity plot. Enhanced soil conservation maintained greater stability with increased plant species diversity. Plant individual density increased linearly and the canopy density and cross section at breast height increased logarithmically with the increase of plant species diversity. The hydrological function enhanced as the plant species diversity increased. There were obviously relationships between plant species diversity and rainfall interception, coverage, and plant individual density, which was related to soil conservation functions in the five forest communities.

The complex relationships between plant species diversity and the above-mentioned ecological processes indicated that plant species diversity was an important factor influencing the interception of rainfall, reducing soil erosion and enhancing the stability of soil conservation, but its mechanism is not known. This experiment showed that plant species diversity promoted soil and nutrient conservation and ultimately lead to the increase of the primary productivity of the ecosystem, and was thus a good way to study the relationship between biodiversity and ecosystem stability. Rainfall interception could be assessed easily using the hygroscopic volume of plant leaves. Because there were strong correlations between plant species diversity and soil conservation functions, the

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patterns of plant species diversity will show a certain level of predictability on the interactions of life systems with surface processes of the Earth.

Keywords biodiversity, ecosystem functions, soil conservation, stability, hydrological effects, community structure

1 Introduction

The relationship between biodiversity and ecosystem functions had been discussed in *Origin of Species* by Darwin 100 years ago (Kareiva, 1996; Zhang and Zhang, 2002). Many ecologists have extensively studied this relationship in the productivity, sustainability, and stability of ecosystem since 1950s, especially 1990s, by using a theoretical approach, by location observation, and by species assemblage experiments (Zhou and Ma, 1990; Chen and Qian, 1997; Huang et al., 2000; Tilman, 2000; Zhang, 2000; Ma et al., 2004). Because the primary productivity of the ecosystem is the key factor affecting ecosystem functions and stability, many ecologists used biodiversity gradients such as loss of species in plant communities to directly test the influences of biodiversity on the productivity of the ecosystem. Their results showed that the productivity of the ecosystem rose with increase in biodiversity (Tilman, 1996). However, there was no “over-yield effect” in the ecosystems of higher biodiversity compared with one species, and did not always have “the same effects” of biodiversity on the primary productivity in the natural ecosystem, which made direct tests get into deadlock (Wardle et al., 1997; Huang et al., 2000; Huston et al., 2000).

Soil conservation is one of the most important functions in the ecosystem and it is directly affected by plant community structure (Chen and Qian, 1997). Plant species diversity is one of the elements of the plant community structure, as it obviously affects the other elements such as canopy coverage, litter, plant individual density, etc. (Spehn et al., 2000; Jiang et al., 2002; Feng, 2003). Because the primary productivity is correlated with the sustainable supply of soil nutrients in the ecosystem, and soil conservation leads to the sustainability of the process, a logical study of the relationship between plant species diversity and the primary productivity of the ecosystem can be used to study the relationship between plant species diversity and soil conservation (William et al., 1983; Tilman et al., 1996). In addition, plant species diversity is the product of creature evolution and Earth history, and studying the relationship between plant species diversity and soil conservation of ecosystem can help us understand the interaction of interfaces of the organism ecosystem and the Earth ecosystem and even predict the change of environment pattern in the past or future. For example, soil erosion is the key ecological process leading to soil organic carbon pool greatly losing in the global change, which takes up about two third–three fourth of the total organic carbon pool; therefore, the study of the relationship between plant species diversity and soil

conservation of the ecosystem can explain the contribution of plant diversity to the control of greenhouse effect in the worldwide context (Schlesinger, 1977, 1997).

Ewell (1986, 1991) ever studied the hydrological processes and soil nutrient dynamic process of the ecosystems at different species diversity levels established by species assemblage under the condition of the same primary soil environment, and his results showed that plant species promoted soil nutrient conservation. Then, Schulze and Mooney (1993) recognized that the experiment was not able to explain the effects of plant species diversity because the plots of the experiment did not control all the factors influencing soil erosion. Naneem and coworkers (1994) set up the ecosystems including producers, consumers, and reducers, and their research contents included the changes of water content; available N, P, and K content in soil; litter decomposition rate; and primary productivity of ecosystem at different biodiversity levels; and they concluded that all the processes were positive related to the biodiversity of ecosystem. Tilman (1996) measured NH_4^+ and NO_3^- concentrations in root zones in assembled plant communities at different diversity levels and found that the concentrations of the available nutrients became lower and lower and the primary productivity got higher and higher with increasing plant species diversity. The causes of decrease in concentrations of the available nutrients were that plant species diversity led to more available N absorbing by the plant root system and low leaching of available N in soil, thus plant species diversity caused nutrient sustainable use and high primary productivity of the ecosystem. Obviously, these two experiments had not verified whether plant species diversity directly related to soil nutrient conservation of ecosystem, and their conclusions were only based on the inference of all experimental results. To verify whether plant species diversity is one of the regulating factors of the soil conservation function of the ecosystem, all other factors affecting soil erosion had to be controlled except plant species diversity, and some soil erosion indices should be measured to analyze the direct relationship between them and plant species diversity.

In order to resolve this, the serial plots that plant species diversity changed gradually were established to observe the surface runoff, soil erosion, total P loss in runoff and the interception rains of canopy, and to investigate vegetation parameters at the secondary succession phases of forest vegetation. The plots have the same soil type and slope position and degree so that all influencing factors on soil erosion were the same and only plant species diversity changed gradually. All observation and investigation data were used 1) to analyze the direct relationship between plant species diversity and soil conservation functions and its stability; 2) to explain how plant species diversity affects soil conservation of the ecosystem based on the logically ecological process the “plant species diversity, plant community structure parameters, interception of rainfalls, soil conservation functions”; and 3) to discuss the ecological significance of the relationship

between plant species diversity and soil conservation functions of the ecosystem.

2 Study site

The study was conducted in Samachang, a small watershed in Muding county of Yunnan province, China (25°24'09"N, 101°28'18"E). The area of the watershed is about 1.8 km². The annual average precipitation is 800–1,300 mm and the precipitation process mainly occurs from May to August every year. The annual average temperature is about 10.4–14.7°C. The type of the soil is purple soil. Communities include AEI (Ass. *Elsholtzia fruticosa* + *Imperata cylindrical*), APMO (Ass. *Pinus yunnanensis* + *Myrsine africana* + *Oplismenus compositus*), APLO (Ass. *Pinus yunnanensis* + *Lithocarpus confines* + *Oplismenus compositus*), AEME (Ass. *Eucalyptus smith* + *Myrsine africana* + *Eupatorium adenophorum*), and ACKV (Ass. *Cyclobalanopsis glaucooides* + *Keteleeria evelyniana* + *Viola duclouxii*). The plant communities are at different secondary succession phases of a semi-humid evergreen broad-leaved forest (Jiang, 1984).

3 Methods

3.1 Vegetation survey

Three 10 m × 40 m “plots” at least were set up at every succession phase and each was selected at the same slope degree and slope position. We recorded all arbor species and measured every stem ≥ 2 cm in diameter at breast height. The living standing crop of branches, leaves, and stems of every species in all plots was determined by relative growth method. Canopy density was measured by CI-110. In each plot, three 4 m × 4 m and 1 m × 1 m subplots were set up and bush and herb species were recorded also. Their living standing crop was determined by harvest. Plant species diversity was evaluated by the number of species in every 10 m × 40 m plot on arbor, bush, and herb layers based on Eq. (1). Because these different secondary succession phases of the semi-humid evergreen broad-leaved forest had lasted for a different succession time, plant species diversity among the plots at different succession phases should show gradual change according to the time hypothesis in the biodiversity theory in ecology (Song, 2001). Vegetation survey concluded when the evaluation showed that the species diversity changed gradually.

$$D = S_i - S_0 \quad (1)$$

where D is the plant species diversity, S_i is the number of the species of plot i different from each other on arbor, bush, and herb layer, and S_0 is the least number of the species different from each other among all plots on arbor, bush and herb layer.

3.2 Measurement of surface runoff, soil erosion, and total P loss

Runoff plots were established around the vegetation survey plots and isolated with concrete buildings treated with waterproof material for protection against the leakage of surface runoff. The plots extended to a depth of 0.5 m under the soil surface and stood 0.3 m high above the soil surface. The major axis of plots was paralleled to longitudinal slope. Runoff collecting trough at the bottom of the plots channeled flow to runoff pools, and at the top of the trough SW40 lim-nimeters were installed to record runoff depth. After raining, the runoff in the pool was mixed adequately and 1,000 mL of runoff at every plot was sampled with layer sampler. The sediment content of runoff was measured by oven drying method. The concentration of total P of runoff was determined by molybdenum colorimetric method. The precipitation was measured by DSJ-2 siphon hyetometer installed on the open land beside the study site and checked by three ordinary hyetometers installed on other open land. The observation lasted from February 2001 to December 2003. Because almost all factors influencing soil erosion, such as slope degree, slope position, precipitation, and soil types, were the same except for plant species diversity among vegetation structure indices, we recognized that the experiment was able to test the effect of plant species diversity on soil conservation function of the ecosystem. The cv values of surface runoff, soil erosion, and total P loss at all plots with the gradual changes of plant species diversity were calculated using Eq. (2) to analyze the stability of soil conservation functions of the ecosystem (Tilman et al., 1996).

$$cv = \frac{100 \times \sigma}{\mu} \quad (2)$$

where cv is the coefficient of variation, σ is the standard deviation of soil conservation indices, and μ is the average value of soil conservation indices. The less the cv , the more stable the ecosystem.

3.3 Measurement of the hygroscopic volume of vegetation

Spiral ditch techniques were usually applied to determine the interception of the rainfalls of forest canopy so as to evaluate its hydrological effects; and the technique is also very convenient to study the interception characteristics of different plant communities under the same or different precipitation conditions (Liu et al., 1991; Liu, 1996; Zhou, 1997). However it is impossible to use it to precisely and microcosmically study the hydrological effects of all different species including small shrubs or herbs in plant communities to evaluate the hydrological function of plant species diversity. Therefore, the determination of the hygroscopic water on the surfaces of plant organs replaced spiral ditch techniques to evaluate the hydrological effect of different species in the plant community. The hygroscopic water is the water drips

and water membranes on the surface of plant organs. Rain drips adhere to their surfaces and produce water membranes while raining or falling into dew. Because the interception of rainfalls by forest canopy consists of the volume of water evaporated into air and absorbed into the plant body, which come from the hygroscopic water on the surface of plant organs, the interception of rainfalls is nothing but the evaporated and absorbed hygroscopic water. More hygroscopic water on the surface of plant organs means more interception of rainfalls. So, the determination of the hygroscopic water on the surface of plant organs should be able to reflect the interception effect of forest canopy. Because leaves play the major role in the hydrological effects among all organs above ground, the present work mainly considered the determination of the hygroscopic water of leaves to evaluate the hydrological effects of forest canopy.

After about 1,000–1,500 g of the samples of leaves of certain species were collected and weighed, they were put on the tela awning put up by a wood frame. Water was sprinkled on the leaves with a sprayer to make their surfaces wet, and in the process the leaves were turned over again and again. As water drips did not drop down from the tela awning, wet samples were at once weighed and the rate of absorption of the hydrosopic water on the samples of leaves of certain species was calculated with Eq. (3).

$$P_{il} = (S_w - S_h) \times 100 / S_h \quad (3)$$

where P_{il} is the rate of absorption of the hygroscopic water on the living samples of the leaves of certain species, S_w is the weight of living samples of the leaves of the species after wetting through by water, and S_h is the weight of the living samples of the leaves of the species before wetted through.

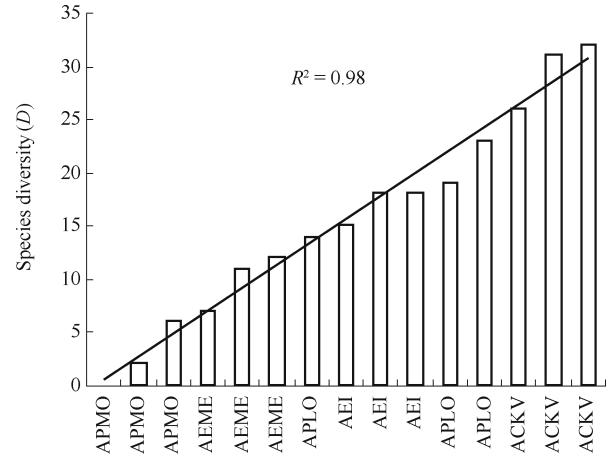
The rate of absorption of the hygroscopic water of plant samples on herb layer was calculated based on the mixed samples of branch and leaves. The gross hygroscopic water of all plants at series plots were calculated according to the rate of the hygroscopic water of every species and the living standing crop of the leaves of every species on arbor and bush layers and of mixed samples on herb layer.

4 Results

4.1 The characteristics of plant species diversity

The data of vegetation survey indicated that total plant species diversity on arbor, bush, and herb layer changed gradually among all plots at different secondary succession phases. Plant species diversity was significantly related to succession time that the different succession phases expressed ($n = 15$, $R^2 = 0.98$, $p < 0.001$). The highest plant species diversity existed in ACKV and APLO containing 60–73 plant species, except a plot of APLO containing 55 plant species. There was middle plant species diversity in AEI whose plots contained 56–59 plant species. There was the lowest plant

species diversity in AEME and APMO whose plots only contained 41–53 plant species (Fig. 1).



APMO: Ass. *Pinus yunnanensis* + *Myrsine africana* + *Oplismenus compsitus*; AEME: Ass. *Eucalyptus smith* + *Myrsine africana* + *Eupatorium adenophorum*; APLO: Ass. *Pinus yunnanensis* + *Lithocarpus confines* + *Oplismenus compsitus*; AEI: Ass. *Elsholtzia fruticosa* + *Imperata cylindrical*; ACKV: Ass. *Cyclobalanopsis glaucoides* + *Keteleeria evelyniana* + *Viola duelouxii*.

Fig. 1 Gradient change of plant species diversity at series plots of different succession phases

4.2 Soil conservation functions of ecosystem

The total precipitation from May to September was 725.66, 828.44, and 734.85 mm in 2001, 2002, and 2003 respectively. The precipitation in 2001 and 2003 was less than that in 2002, but the most precipitation occurred on June 29, 2003 (127.4 mm). Surface runoff, soil erosion, and total P loss were highest at the plots of APMO and lowest at the plots of ACKV, and their average values for three years were 661.22 m³/(hm²·year), 5.96 t/(hm²·year), 104.52 kg/(hm²·year) for APMO and 91.23 m³/(hm²·year), 1.29 t/(hm²·year), 7.71 kg/(hm²·year) for ACKV. The indices of the plots in APMO were 3–10 times higher than those in ACKV. Soil conservation functions of APMO were very similar to those of AEME because surface runoff, soil erosion, and total P loss of the plots of APMO were only 1–2 times higher than those of AEME. Soil conservation functions of AEI and APLO were intermediate among all succession phases, but APLO was a bit stronger than AEI. These results showed that soil conservation functions were enhanced with plant community succession. The natural regeneration of AEI, bush and herb vegetation, was better than artificial regenerations of APLO and AEME on soil conservation functions of the ecosystem (Table 1).

4.3 Plant species diversity and soil conservation functions of ecosystem

The surface runoff occurrence frequency at different succession phases decreased with the increase of plant

Table 1 Surface runoff, soil erosion, total P loss at different phases

Variables of soil conservation	Years	Rainfall /mm	Runoff rainfall /mm	The greatest rainfall /mm	APMO	AEME	AEI	APLO	ACKV
Surface runoff /($\text{m}^3 \cdot \text{hm}^{-2} \cdot \text{year}^{-1}$)	2001	715.66	422.00	44.50	596.68	358.68	192.36	157.87	109.78
	2002	828.44	542.99	127.40	767.35	377.59	251.03	129.25	40.38
	2003	734.85	612.20	79.60	619.63	379.13	308.13	202.43	123.55
	Average	759.65	525.73	—	661.22	371.80	250.50	163.18	91.23
Soil erosion /($\text{t} \cdot \text{hm}^{-2} \cdot \text{year}^{-1}$)	2001	715.66	422.00	44.50	4.89	4.14	1.95	1.60	1.31
	2002	828.44	542.99	127.40	6.59	4.81	2.89	1.48	1.18
	2003	734.85	612.20	79.60	6.40	4.70	1.99	1.47	1.40
	Average	750.65	525.73	—	5.96	4.55	2.27	1.51	1.29
Total P loss of runoff /($\text{kg} \cdot \text{hm}^{-2} \cdot \text{year}^{-1}$)	2001	715.66	422.00	44.50	73.89	72.62	25.63	19.69	10.40
	2002	828.44	542.99	127.40	112.96	93.58	38.23	35.39	7.26
	2003	734.85	612.20	79.60	126.71	75.32	29.03	19.34	5.47
	Average	750.65	525.73	—	104.52	80.51	30.96	24.81	7.71

AMPO, APLO, AEME, AEI, ACKV, see Fig. 1.

species diversity under the same influencing factors such as precipitation, slope degree, slope position, etc., and plant species diversity was obviously negative related to surface runoff occurrence frequency ($n = 15$, $r = -0.96$, $p < 0.001$). At the interval of observation, APMO with the lowest plant species diversity that produced the most times of surface runoff and the total was 77 times—23, 32, and 22 times in 2001, 2002, and 2003 respectively. AEME and APLO produced almost the same rates of surface runoff, in that their plant species diversity was relatively near. The succession phase that produced the least rate of surface runoff was ACKL with the highest plant species diversity, which only did 9 times of surface runoff—2, 4, and 3 times in 2001, 2002, and 2003 respectively. The succession phase APLO and AEI with intermediate plant species diversity produced intermediate rates of surface runoff (Fig. 2).

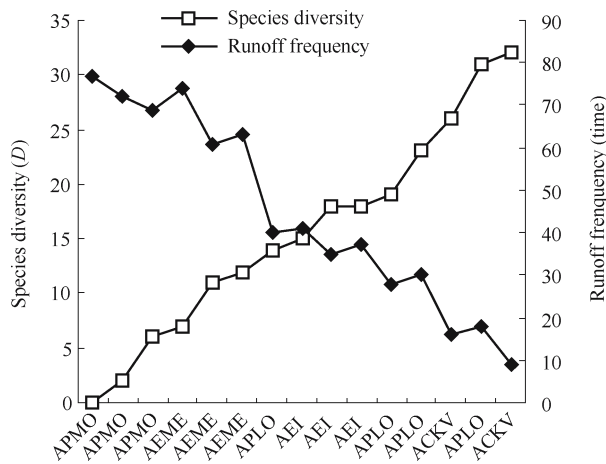


Fig. 2 Plant species diversity and runoff frequency at different succession phases

AMPO, APLO, AEME, AEI, ACKV, see Fig. 1.

Surface runoff, soil erosion, and total P loss decreased as a power function as plant species diversity increased and the correlation between plant species diversity and them was very significant (A: $n = 77$, $r^2 = 0.67$, $p < 0.005$; B:

$n = 77$, $r^2 = 0.71$, $p < 0.001$; C: $n = 77$, $r^2 = 0.77$, $p < 0.0001$). The average values for 3 years were $960.20 \text{ m}^3/(\text{hm}^2 \cdot \text{year})$, $11.40 \text{ t}/(\text{hm}^2 \cdot \text{year})$, and $127.69 \text{ kg}/(\text{hm}^2 \cdot \text{year})$ in the plot with lowest species diversity, and $75.55 \text{ m}^3/(\text{hm}^2 \cdot \text{year})$, $0.28 \text{ t}/(\text{hm}^2 \cdot \text{year})$, and $4.71 \text{ kg}/(\text{hm}^2 \cdot \text{year})$ in the plot with the highest species diversity. The low species plot was respectively 12, 50, and 25 times higher than the high species plot. When rainfall increased, the low species plots produced a great amount of surface runoff but the high species diversity plots generated less surface runoff. Under the relatively intermediate amount of the precipitation condition, the low species diversity plots still produced more surface runoff, but the high species diversity plots produced much less surface runoff or even no surface runoff. Under the small precipitation condition, the low species diversity plots produced little surface runoff, and the high species diversity plots did not generate runoff at all. Total P loss and soil erosion of all plots showed the same characteristics as surface runoff.

The cv values of surface runoff, soil erosion, and total P loss decreased continually with the increase of plant species diversity (Fig. 4), which followed a power function and the correlation between cv and plant species diversity was very significant (A: $n = 15$, $r^2 = 0.45$, $p < 0.01$; B: $n = 15$, $r^2 = 0.71$, $p < 0.001$; C: $n = 15$, $r^2 = 0.47$, $p < 0.01$). The cv values of surface runoff, soil erosion, and total P loss were respectively 287.6, 534.21, and 315.47 in the lowest species diversity plot and 57.93, 187.94, and 59.2 in the highest species diversity plot, and was 4, 3, and 5 times lower than those in the lowest species plot. The result indicated that increasing plant species diversity maintained greater stability of soil conservation functions of the ecosystem. There was significant difference among cv values of surface runoff, soil erosion, and total P loss of the plots. The cv value of soil erosion was greater than that of surface runoff and total P loss, and showed that the stability of the soil erosion process of the ecosystem was lower than that of surface runoff and total P loss at the same diversity levels. The result also showed that the soil erosion process was more complicated than the processes of surface runoff and total P loss.

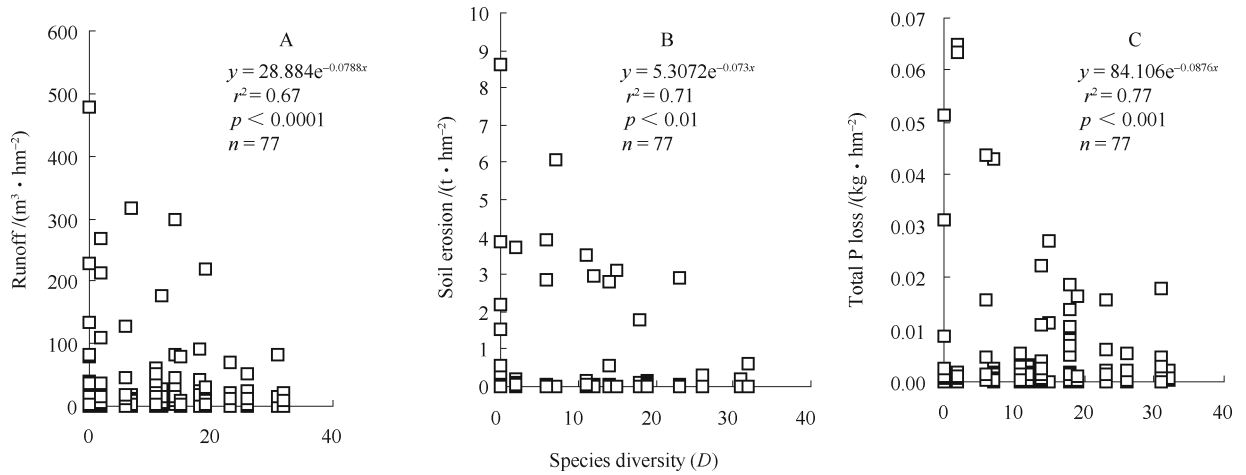


Fig. 3 Plant species diversity and surface runoff, soil erosion and total P loss at the series plots with increasing plant species diversity. Dot diagrams drawn with 77 times of the observation values of surface runoff, soil erosion and total P loss against plant species diversity, D , at series plots. Surface runoff did not happen at some plots at high plant species diversity level and the observation values were 0 but surface runoff happened at low plant species diversity. Based on the observation value the correlation between plant species diversity, D and the observation value was tested.

A: plant species diversity and surface runoff; B: plant species diversity and soil erosion; C: plant species diversity and total P leaching.

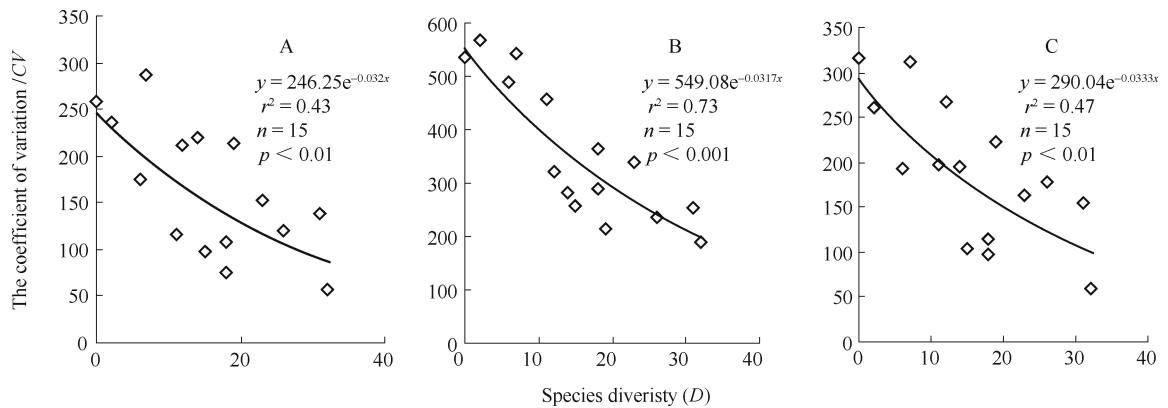


Fig. 4 Relation of plant species diversity to the coefficient of the variation of surface runoff, soil erosion and total P loss at the series plots. Figures drawn with the coefficient of variation of 77 times of the observation values of surface runoff, soil erosion and total P loss against plant species diversity, D , at the series plots. Surface runoff did not happen at some plots at high plant species diversity level and the observation values were 0 but surface runoff happened at the plots at low plant species diversity level. Based on the calculation results the correlation between plant species diversity and coefficient of variation was tested. A: surface runoff; B: soil erosion; C: total P loss.

4.4 The relationship between plant species diversity and plant individual density, canopy density, cross section areas at the breast height

Plant individual density of community went up linearly with the increase of plant species diversity and the test of the correlation between them showed very significant results ($n = 15$, $r^2 = 0.87$, $p < 0.001$, Fig. 5). The relationship between them could be simulated by $y = ax + b$. The result was consistent with the research in Hainan Island of China (Jiang et al., 2000). We suggested that plant species diversity resulted in the increase of plant individual density. Because the maintenance of plant species diversity relied on environment heterogeneity, which led to more species distribution and

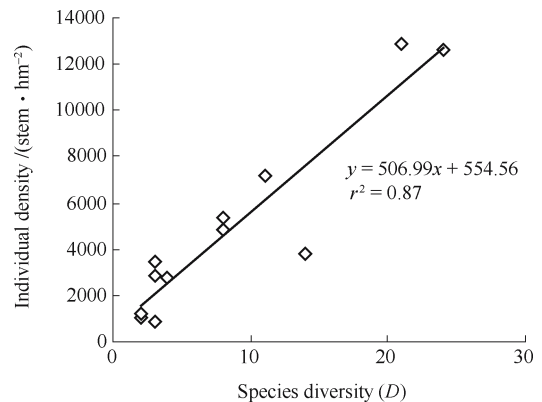


Fig. 5 Plant species diversity and individual density

coexistence in an ecosystem, it implied that the ecosystem had a high loading ability of plant species. In limited space, many plant species' coexistence intensified inter-specific competition and the space niche of every species tended to become little. However, the maintenance of every species in the ecosystem depended on the least population, in that if the population of a species were less than its least population, the species would be partly extinct. Therefore, every species may tend to take the adaptive ecological strategies to maintain the population in competition. This led to the increasing of total plant individual number in ecosystem.

The canopy density and cross-section area at the breast height increased logarithmically with the increase of plant species diversity ($y = a \ln x + b$) and their correlation with plant species diversity was also considerably significant ($n = 15, r^2 = 0.75, p < 0.001; n = 15, r^2 = 0.77, p < 0.001$, Fig. 6). According to the physical meaning of logarithm, the canopy density and cross-section area at the breast height would be up to their extreme value with the increase of plant species diversity. When species diversity was 25, the canopy density was 80% and cross-section area at the breast height was 33, and they almost stopped rising with the increase of plant species diversity. So the values of 80% and 33 seemed to be the extreme values of these two variables. The relationship between plant species diversity and the canopy density and cross-section area was similar to the relationship between plant species diversity and plant individual density. The inter-specific competition of plants was intensified for plant species diversity in the ecosystem and every species tended to expand horizontally and vertically in the new niche to occupy more resources and space; as a result, the number of the vertical layers and coverage of the plant community increased. These processes affected the canopy density and cross-section area at the breast height.

4.5 The relationship between plant species diversity and the hygroscopic water of leaves

The hygroscopic volume of leaves was considerably different among the different succession phases (Table 2). The

hygroscopic volume of ACKL, AEI, AEME, APLO, and APMO was respectively 12.28, 4.15, 7.59, 6.21, and 5.67 t/hm² and equaled to 1.23, 0.42, 0.76, 0.62, 0.57 mm of precipitation respectively. The hygroscopic volumes of ACKL and APMO were respectively the greatest and the least among all the succession phases and that of AEME, APLO, and APMO were intermediate. The hygroscopic volume of the plant community increased continually over the community succession process. The hygroscopic volume of the coniferous forest was less than that of the broad-leaved forest. These results were similar to some past works carried out using spiral ditch techniques to determine the interception of rainfalls in the semi-humid evergreen broad-leaved forest in Yunnan of China (Liu et al., 1991).

Table 2 Hygroscopic volume of the leaves of forest canopy at the different secondary succession phases

Succession phases	Hygroscopic volume /(t·hm ⁻²)		
	Woody plant layer	Herbaceous plant layer	Total
AEI	0.56	5.11	5.67
APMO	3.41	0.74	4.15
APLO	5.28	0.93	6.21
ACKV	11.87	0.41	12.28
AEME	6.15	1.444	7.59

The hygroscopic volume of the different phases was also correlated positively to plant species diversity. The hygroscopic volume of woody plants showed a linear relation to plant species diversity ($n = 15, r^2 = 0.49, p < 0.01$), but on the herb layer the relation imitated a power function ($n = 15, r^2 = 0.69, p < 0.001$). When the species number was 40 and the hygroscopic volume was still rising on the woody plant layer, the hygroscopic volume reached the extreme value on herb layer (Fig. 7). The result indicated that the hydrological function becomes strong with the increase of plant species diversity, and plant species diversity predicted the decrease of rain drip energy acting on the soil surface and the dying down of the erosion process.

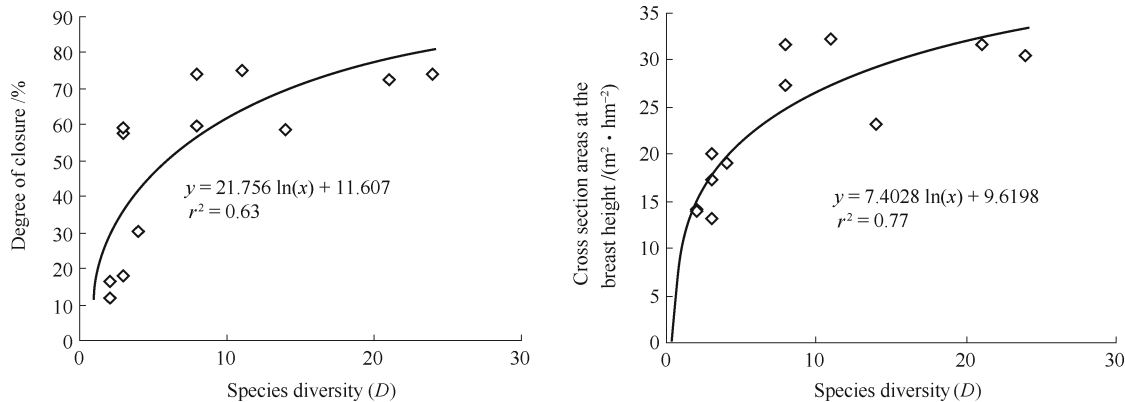


Fig. 6 Relationship between plant species diversity and the canopy density and cross section area at the breast height at plot scales at the different succession phases of semi-humid evergreen forest.

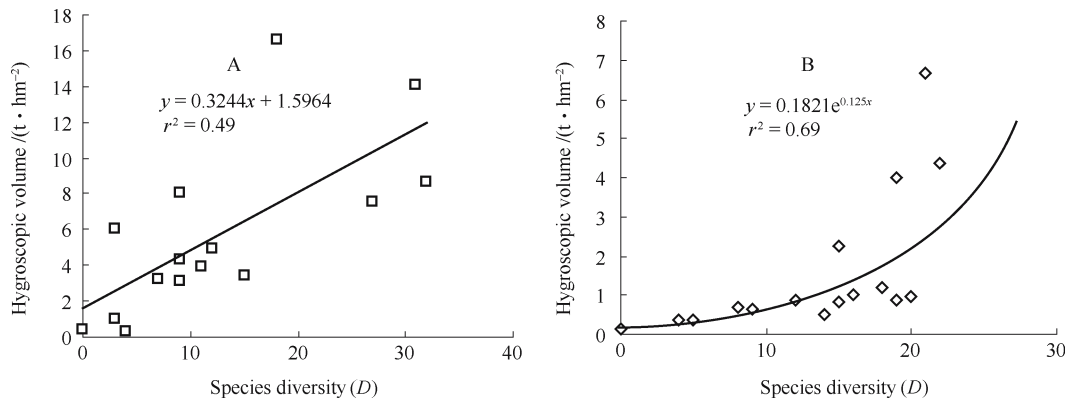


Fig. 7 Plant species diversity and the hygroscopic volume of the leaves of forest canopy on woody plant layer (A) and herbaceous plant layer (B).

5 Discussion

5.1 Plant species diversity and soil conservation functions

Surface runoff, soil erosion, and total P loss went down with the increase of plant species diversity and there was obvious negative correlation between plant species diversity and these variables. Because all factors influencing soil erosion, such as precipitation, slope degree, slope position, soil types, were the same except for plant species diversity in vegetation structure variables, the result directly verified the prediction that plant species diversity was directly related to soil nutrient conservation, which supported Naeem's points (Naeem et al., 1994), i.e., plant species diversity was able to lead to the sustainability of soil nutrients and productivity of the ecosystem. The correlation between plant species diversity and soil conservation function also explained why there was high concentration of organic carbon, total nitrogen, and dissolved calcium in assembled ecosystem with high plant diversity (Ewell, 1986; Ewell et al., 1991; Schulze et al., 1991).

In experiment, the effects of plant species diversity on soil conservation could not be isolated from the effects of different secondary phases of vegetation. However, plant community types were classified based on the dominance of plant species with different phenotypes in the community, especially, dominant species that played a major role in the plant community. Increasing plant diversity meant increasing the difference of plant species in the plant community. The difference of species was the result of phylogenetic development, such as plant phenotypic difference depending on genetic variability and ecological diversity of species and so on. In taxonomy, the difference of species was the key factor deciding the species and affecting the evaluation of plant species diversity in the vegetation survey (Purvis and Hector, 2000). The difference of plant community became obvious as well, whereas the difference of species was accumulated with the increase of plant species diversity. Some key species would emerge in the plant community with the high probability of making the community different from the original one, such as different succession phases of plant community. Vegetation

type was, to some extent, the expression of plant species diversity changes. Increasing species diversity meant naturally increasing species difference at the serial plots of plant diversity gradient changes. As a result, the identity of vegetation types changed at last. Therefore, the effects of vegetation types on ecosystem functions were also the effects of plant species diversity.

5.2 Plant species diversity and the stability of soil conservation functions of ecosystem

The concept of ecosystem stability was differently understood. But the change range and resilience of the ecosystem after being disturbed by disturbance factors were the most basic connotation (May, 1973; Zhou and Ma, 1990). The coefficient of variation, cv , was an important index that was applied to the theoretical derivation, species assemblage experiment, and field observation to explain the relationship between ecosystem stability and biodiversity (May, 1973; Tilman et al., 1996). It was able to express the deviation degree of observation values from the average value. Small cv value meant small deviation from the average value and the ecosystem tended to stability. The index might be applied to compare the stability of different ecosystem variables under the same condition of plant diversity. According to the researches in the last 10 years, ecosystem stability might be classified into three types (Yue and Ma, 1991; Huang, 1995; Huang et al., 2000; Zhang, 2000; Ma et al., 2004; Wang et al., 2004). The first type was the reaction of the ecosystem to the outside disturbance; for example, the performance of the ecosystem when drought, fire disaster, and other human disturbance occurred. The change range, resistance, and resilience of ecosystem were the important indices evaluating the ecosystem stability. The second type dealt with the relationship between biodiversity change and ecosystem performance. Mathematical method was the important tool to study the types of ecosystem stability. In the field experiment, the performance of the ecosystem was often tested by the change of food net structure. The disturbance of the third stability came from outside and inside the ecosystem and the research work in the 1990s made use of species assemblage to integrate the first and second types.

The stability of the soil conservation function should be classified into the first type of stability. The same precipitation condition might be regarded as a kind of disturbance to the plots at the different plant diversity levels and the change of soil conservation was a kind of reaction on the disturbance. The result indicated that *cv* of surface runoff, soil erosion, and total P erosion became small with the increase of plant species diversity and the stability of soil conservation function was enhanced. The conclusion was the same as that of most of stability researches in ecology and there were fewer issues for the first type. So far, there were more issues for the second and third types. The theoretical researches showed that a simple system was more stable than a complicated one. The complexity of food net structure might lead to ecosystem stability, but there were also opposite conclusions in many researches (McCann et al., 1999). The issue focus of the third type stability lied in the contribution of dominant species to ecosystem function under the condition of increasing biodiversity. Some ecologists recognized that it should be the effect of biodiversity, but there were also some ecologists holding different views (Huston, 2000; Tilman, 2000).

The relationship between plant species diversity and soil conservation functions might be applied to study the complicated stability of the ecosystem because there were substance outputs from the ecosystem and the same “disturbance” of precipitation in the ecosystem. Based on the output of life element, same rainfall conditions in the watershed ecosystem, and the manmade regulation of food net structure many types of stability of the ecosystem can be finally analyzed and integrated.

5.3 Plant species diversity and community structure-interception of rainfalls-soil conservation of ecosystem

Soil conservation was affected by precipitation, terrain, soil property, and vegetation. Under the same precipitation, landform, and soil property, vegetation was only a factor influencing soil conservation. Increases of vegetation coverage, individual density, cross-section area at breast height, and litter amount were able to enhance the interception of rainfalls, lighten soil splash erosion in exhaust rain-drip energy, and strengthen the resistance of soil erosion (Liu et al., 1996; Wang, 1997; Wang et al., 2001). In our work, plant individual density increased linearly, canopy density increased as a power function, and cross-section area at breast height increased logarithmically with the hygroscopic volume of leaves rising continually; and soil conservation function was enhanced with the increase of plant diversity at the serial plots. These processes indicated that when plant species diversity increased, plant community structure produced the changes benefiting the lightening of rain-drip splash erosion and the control of surface runoff and soil erosion. The correlated processes could be interpreted by the deterministic and stochastic process of species diversity (Loreau et al., 2001). Spehn et al. (2000) found that the average height of herb community rose by about 46% and the gravitation center of the community went up by about 10 cm with plant species

number change from 1 to 32. The layers, leaves area index of the community, and coverage of the plant community all increased with the increase of plant diversity (Jiang et al., 2002). The earlier work showed that the plant community contained more life forms and layers of community with the increase of plant diversity and the stretch way of branch and leaves became more complex. Plant individual density significantly increased with the increase of plant diversity in Hainan tropical zone forest as well (Zhu et al., 1988; Jiang et al., 2000). Therefore, the plant community structure tending to be complex with the increase of plant species diversity was a universal process in the ecosystem, and led to more interception of rainfalls and exhaust of rain drip energy. At last the effect of plant diversity embodied the lightening of soil erosion and nutrient loss. “Plant species diversity–community structure change–interception of rainfalls–soil conservation enhances” was a logical ecological process. Plant species diversity indirectly regulated soil erosion and nutrient loss through plant community structure. Because intense soil erosion was sure to lead to decrease in the primary productivity, the logical relation verified that the loss of plant species diversity meant a decrease of the primary productivity in the land ecosystem. This should become a new explanation about “biodiversity–primary productivity hypothesis.”

In addition, plant species diversity should be able to regulate plant root system structures according to the relative growth law of plants besides regulating the plant community structure above ground. The density of root system, stretch way, angle, and match way may vary with plant species diversity (Feng, 1999). Because the change of the space structure of root system will directly affect soil dynamics and resistance to soil erosion related to soil conservation function and stability, these changes will have a great impact on soil conservation process. But how plant diversity regulates root system structure and soil dynamics needs to be studied further.

5.4 The ecological significance of the study of the relationship between plant species diversity and soil conservation functions

The study on the relationship between plant species diversity and soil conservation functions can promote us to understand the interaction between interfaces of the life and Earth system besides the argument of the relationship between plant diversity and productivity and stability of the ecosystem, because plant diversity is the product of Earth’s history. In the evolution of life, biodiversity rose in general and simultaneously the Earth’s environment also changed continually from reductive state at the early period to oxidized state at a later period, from the control of geological cycle (intense erosion, transport, sediment, Earth crust rise) to biochemical cycle (substance cycle among organisms and plant control intense erosion). The affection of life system and diversity on these processes led to the modern environmental pattern. After understanding the relationship between plant diversity and

soil conservation function and the regulation model plant diversity acting on the soil erosion process, the information of plant diversity in early, modern, and future periods perhaps may be used to predict the biogeochemical process velocity and environment pattern of different periods.

6 Conclusions

There was a direct relationship between plant species diversity and soil conservation functions. Plant species diversity obviously regulated plant community structure, whereas plant community structure affected soil conservation process. Higher plant species diversity led to the better performance of soil conservation functions and maintained the stability of the function. Because of the worldwide acceptance that soil erosion on the land ecosystem at different scales leads to the decrease of the primary productivity, the high plant diversity of the ecosystem improves the primary productivity of the ecosystem. The study on the relationship between plant species diversity and soil conservation functions could help us understand the stability of ecosystem, and the interaction between interfaces of life system and Earth system besides the argument of the relationship between plant diversity and productivity and stability of ecosystem.

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