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Changes of Soil Water, Organic Matter, and Exchangeable Cations Along a Forest Successional Gradient in Southern China[*1]

YAN Jun-Hua, ZHOU Guo-Yi, ZHANG De-Qiang and CHU Guo-Wei

South China Institute of Botany, Chinese Academy of Sciences, Guangzhou 510650 (China). E-mail: jhyan@scib.ac.cn

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ABSTRACT

Information on the distribution patterns of soil water content (SWC), soil organic matter (SOM), and soil exchangeable cations (SEC) is important for managing forest ecosystems in a sustainable manner. This study investigated how SWC, SOM, and SEC were influenced in forests along a successional gradient, including a regional climax (monsoon evergreen broad-leaved forest, or MEBF), a transitional forest (coniferous and broad-leaved mixed forest, or MF), and a pioneer forest (coniferous Masson pine (*Pinus massoniana*) forest, or MPF) of the Dinghushan Biosphere Reserve in the subtropical region of southern China. SWC, SOM, and SEC excluding Ca^{2+} were found to increase in the soil during forest succession, being highest in the top soil layer (0 to 15 cm depth) except for Na^+. The differences between soil layers were largest in MF. This finding also suggested that the nutrients were enriched in the topsoil when they became increasingly scarce in the soil. There were no significant differences ($P = 0.05$) among SWC, SOM, and SEC. A linear, positive correlation was found between SWC and SOM. The correlation between SOM and cation exchange capacity (CEC) was statistically significant, which agreed with the theory that the most important factor determining SEC is SOM. The ratio of K^+ to Na^+ in the topsoil was about a half of that in the plants of each forest. MF had the lowest exchangeable Ca^{2+} concentration among the three forests and Ca^{2+}:K^+ in MPF was two times higher than that in MF. Understanding the changes of SWC, SOM, and CEC during forest succession would be of great help in protecting all three forests in southern China.

Key Words: forest succession, soil exchangeable cations, soil organic matter, soil water content

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INTRODUCTION

The natural forests in China have been under continuous change since the Chinese government set up the Natural Forest Conservation Program (NFCP) a few decades ago. Forest ecosystems undergo changes in its community structure, species composition, abundance, and consequently the biogeochemical cycles. Among all these changes, the structure alterations by forest development and succession are most significant. The effects of forest succession also include modified biogeochemical cycles and many changes in soil chemical and physical properties (Bakker *et al.*, 1997; Sheil, 2001). Compared to the apparent structure changes aboveground, the changes in soil properties are less conspicuous, but equally important (Jobbagy and Jackson, 2001). These changes provide useful information for the natural forest management and protection. Meanwhile, investigation on the variations of soil water content (SWC), soil organic matter (SOM), and soil exchangeable cations (SEC) can provide insights into their input, output, and cycling processes for global change research (Rosenzweig and Hillel, 2000).

Soil water is the main water source for plant growth and is recharged through underground water, throughfall, and stem flow. Changes in SWC may significantly influence the tree species diversity and forest canopy structure (Meszaros *et al.*, 2005). Therefore, forest succession could dramatically alter SWC through the accumulation of vegetation biomass. SOM is widely regarded as a vital component

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of a healthy soil. It influences many of the physical, chemical and biological properties of soil. SOM accumulation in soil is believed to be a significant process in the global carbon cycle, and the ameliorated soil provides a suitable environment for the establishment of late succession species (Li *et al.*, 1999). In recent years, increases of atmospheric carbon dioxide, changes of land management practices, and acute interest in the global carbon cycles have attracted significant attention to SOM dynamics. Soil exchangeable cations (SEC) are a general indicator of soil storage capacity for available, positively charged plant nutrients such as K, Na, Ca, and Mg. Their distributions are usually related to plant activities. As long as SEC uptake by plants takes place at a greater depth than the returns to the soil, a net uplift should be expected. On the other hand, if the magnitude of SEC uptake by plants is less than the other processes such as leaching, it will be transported from the soil surface to the deep soil (Jobbagy and Jackson, 2004).

Studies on the SWC, SOM, and SEC changes have often been executed in agricultural soils (Li *et al.*, 2000). Unlike the agricultural ecosystems, the SWC, SOM, and SEC changes in forest soils are poorly understood (Chen *et al.*, 2005). The subtropical forests in South China are unique under the influence of monsoons from the western Pacific and north Indian Oceans (Kong *et al.*, 1997). A regional forest community, subtropical monsoon evergreen broad-leaved forest (MEBF), as well as its transitional succession community, coniferous and broad-leaved mixed forest (MF), and its pioneer coniferous Masson pine (*Pinus massoniana*) forest (MPF) in the Dinghushan Biosphere Reserve, which represent a typical succession series with pioneer to climax vegetation communities in this region, have been protected from any significant human disturbance (Peng and Wang, 1995). The soils in all three forests are developed under the uniform bedrock. Thus, the differences of distribution patterns of SWC, SOM, and SEC among all forest stands result from forest succession and relevant biological processes. An improved understanding of these distribution patterns is essential for the mechanistic basis of forest management and vegetation rehabilitation. The objective of this study was to evaluate how forest succession affected the distribution patterns of SWC, SOM, and SEC in forest soils of the Dinghushan Biosphere Reserve, to provide policy makers with information on how to manage the forest ecosystems in a sustainable way.

MATERIALS AND METHODS

The Dinghushan Biosphere Reserve (23° 09′ 21″–23° 11′ 30″ N, 112° 30′ 39″–112° 33′ 41″ E) is located in the central part of Guangdong Province, South China, about 84 km west of Guangzhou. The total area of the reserve is 1 156 ha. Most of the Dinghushan area is covered with rolling hills and low mountains, with the altitude ranging from 100 to 700 m. Jilongshan is the highest point with an altitude of 1 000 m. The rock formations of the area are composed of sandstone and shale belonging to the Devonian Period. This reserve has a typical, subtropical monsoon, humid climate with an average annual temperature of 20.9 °C. The highest and lowest monthly mean temperatures are 28.0 °C in July and 12.0 °C in January, and the highest and lowest extreme temperatures are 38.0 °C and −0.2 °C, respectively. The average annual precipitation is 1 956 mm, of which more than 80% falls in the wet season (April to September) and less than 20% in the dry season (October to March). Mean annual relative humidity is 82%. The predominant soil type in the reserve is lateritic red soil, between the elevations of 400 to 500 m, followed by yellow soil, which is found between the elevations of 500 to 800 m. The soil pH is 3.8 to 5.5 and a rich humus layer is common. In the biosphere reserve, there are three types of natural vegetation communities: MEBF with stand age of more than 400 years, MF and MPF, which are considered to represent different succession stages, with MEBF being the climax community (Table I). The flora includes 260 families, 864 genera, and 1 740 species of wild plants.

Seven neutron probes were located within each forest (MPF, MF, and MEBF) for SWC data collection since 1998. During the wet season, SWC was measured every five days, whereas this was done once every week for the dry season.

In each forest, eight replicate cores were sampled using a plexiglass piston corer (diameter 12 cm, length 1.5 m) quarterly in March, June, September, and December since 2002. Surface litter layers were

TABLE I

Some characteristics of the three forests of the Dinghushan Biosphere Reserve

Forest[a]	Elevation	Soil pH	Stand age	Leaf area index	Dominant species
	m		years		
MPF	200–300	3.92	50–60	4.3	*Pinus massoniana*, *Rhodomyrtus tomentosa*
MF	220–300	3.86	About 110	6.5	*Pinus massoniana*, *Schima superba*, *Castanopsis chinensis*
MEBF	220–300	3.96	About 400	7.8	*Castanopsis chinensis*, *Schima superba*, *Cryptocarya concinna*, *Machilus chinensis*, *Cryptocarya chinensis*

[a] MEBF: the regional forest community, subtropical monsoon evergreen broad-leaved forest; MF: the transitional succession community, coniferous and broad-leaved mixed forest; and MPF: the pioneer coniferous Masson pine (*Pinus massoniana*) forest.

not taken into account. The sampled cores were separated into four layers, 0–15, 15–30, 30–60, and 60–90 cm, respectively, which were each wrapped and taken to the laboratory. Five samples of each forest were used for determination of SOM using the common ignition method: The weight loss from a dry soil sample was measured when the constant weight was obtained at a high temperature (165 °C). The weight loss at this temperature was correlated to the oxidizable organic carbon. The other three samples were dried in the air and analyzed for exchangeable Ca^{2+}, Mg^{2+}, K^+, and Na^+ using the standard soil protocols. These included extraction of exchangeable Ca^{2+}, Mg^{2+}, K^+, and Na^+ using 1 mmol L^{-1} CH_3-$COONH_4$. The concentrations of Ca^{2+}, Mg^{2+}, K^+, and Na^+ in the extracts were measured by inductively coupled plasma-atomic emission spectrometry (ICP-AES). SEC had also been measured in each season since 1999.

Data were analyzed using the SigmaPlot (Version 9.0) and SPSS (Version 13.0).

RESULTS AND DISCUSSION

Soil water content distributions

Soil water dynamics for all three forests had been studied for the periods 1983 to 1988 and 1998 to 2003 by Zhou *et al.* (2004). Their results showed that SWC was lower during the latter period in all three forest communities. The negative slopes of regression lines fitted the observations and suggested a long term decrease in SWC, in addition to the seasonal fluctuations associated with climate variation (Zhou *et al.*, 2004). However, SWC always increased in the course of forest succession (Fig. 1). The average SWC for the period 1998 to 2004 at all depths (0–90 cm) was 130 g kg^{-1} in the pioneer MPF, 168 g kg^{-1} in the transition MF, and 197 g kg^{-1} in the climax MEBF. More SWC in the later succession forest stands might imply that the water storage of these forest ecosystems increased because of changes in the soil structure and litterfall cover. The distribution curves of SWC with depth clearly showed that the topsoil layer (0–15 cm) had the highest SWC in each forest. SWC in the 75–90 cm layer was about 64% of the topsoil layer in MEBF. This number increased in MPF and MF, up to 73%.

The above results suggested that forest succession increased both SWC and its vertical variation in the soil. The net SWC uplift from the deeper soil layers to the topsoil as a result of forest succession was a new finding in this study. The annual average evapotranspiration for MPF, MF, and MEBF is 951, 924 and 823 mm, respectively, and increases along with forest succession (Zhou *et al.*, 2004), as required by the water balance. It could be estimated that the climax forest must reduce the runoff for complementing higher SWC and evapotranspiration. The natural succession represented by all three forest types therefore was an evolution towards a relatively more conservative hydrological system, which minimized water export by runoff and reduces the loss of organic matter *via* runoff.

In the previous study, the canopy interception for the three forests is 261 mm in MPF, 454 mm in MF and 573 mm in MEBF (Zhou *et al.*, 2004). Therefore, it was calculated that the contribution of soil

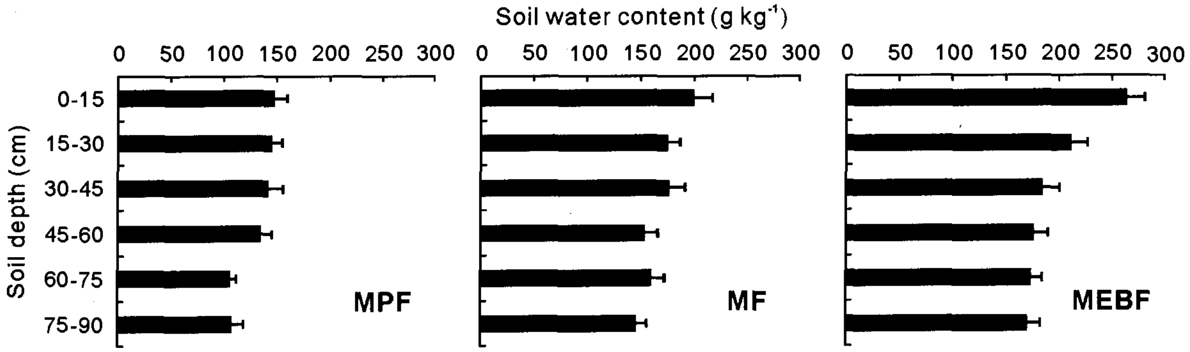

Fig. 1 Soil water content distributions in the three successional forests of the Dinghushan Biosphere Reserve for the period 1998 to 2004: the regional forest community, subtropical monsoon evergreen broad-leaved forest (MEBF); the transitional succession community, coniferous and broad-leaved mixed forest (MF); and the pioneer coniferous Masson pine (*Pinus massoniana*) forest (MPF). Error bar represents one standard deviation.

water to evapotranspiration in MPF, MF, and MEBF were 558, 470, and 378 mm, respectively. It could be inferred that the higher SWC in the later succession forest resulted from the fraction of evapotranspiration derived from soil water decrease with forest succession.

Soil organic matter distributions

In addition to its role in the C cycle, SOM exerts an important influence on soil physical and chemical properties such as acid-base chemistry, pH, buffer capacity, cation exchange capacity (CEC), and metal complexion and transport. The seasonal variation of SOM for all three forests is summarized in Fig. 2. There were no significant seasonal variations for all three forests; SOM increased progressively during forest succession, being highest in the MEBF followed by MF and MPF. These results are in agreement with the well-known positive effect of forest succession on SOM accumulation process (Bakker *et al.*, 1997; Guggenberger and Zech, 1999; Cerri *et al.*, 2004). SOM tended to decrease with soil depth, being

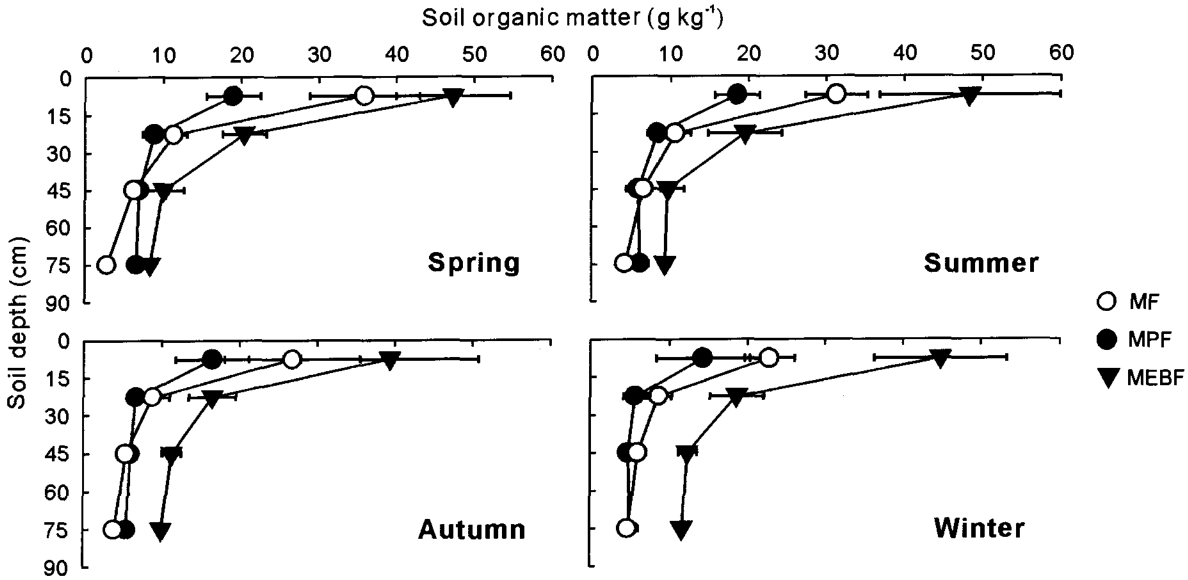

Fig. 2 Mean soil organic matter contents in the three successional forests of the Dinghushan Biosphere Reserve for each of the four seasons (2002–2004): the regional forest community, subtropical monsoon evergreen broad-leaved forest (MEBF); the transitional succession community, coniferous and broad-leaved mixed forest (MF); and the pioneer coniferous Masson pine (*Pinus massoniana*) forest (MPF). Error bar represents one standard deviation.

maximum in the topsoil and minimum in the 60–90 cm layer. For all three forests, the largest difference of SOM content occurred in the topsoil layer and it was relatively constant in the 30–60 cm layer. The nonlinear decrease in SOM, as a function of the depth, was similar in all three forests. The larger variations between different soil layers were found in MEBF. As a transition forest during forest succession in the subtropical zone, MF had the most remarkable difference of SOM content between the topsoil and the 60–90 cm layer. In this forest, SOM in the topsoil layer was seven times more than that in the 60–90 cm layer.

Soil exchangeable cation distributions

Only a small percentage of the essential plant nutrient cations (K^+, Na^+, Ca^{2+}, and Mg^{2+}) are soluble in the soil water and thus available for plant uptake. Thus soil exchangeable cations are important because they provide a reservoir of nutrients to replenish those removed from the soil water by plant uptake. Similarly, cations in the soil water that are leached below the rooting zone by excess rainfall or irrigation water are replaced by cations formerly bound to SEC. Although exchangeable K^+ in MF and MEBF varied significantly between the soil layers, no significant differences along the soil profile were observed in MPF (Fig. 3a). MF and MEBF had substantially higher concentrations of exchangeable K^+ in the topsoil. The amount of exchangeable K^+ of the topsoil layer in MEBF was three times that of MPF. Similar to SOM, exchangeable K^+ varied most in the topsoil layer and was relatively constant in the 60–90 cm layer for all three forests. However, exchangeable Na^+ showed smaller change in the topsoil layer and larger change in the deeper layers among all three forest stands (Fig. 3b). MEBF has two to three times more exchangeable Na^+ in the 60–90 cm layer than MPF and MF. These patterns likely reflected the combined effects of water uptake and Na^+ exudation by trees.

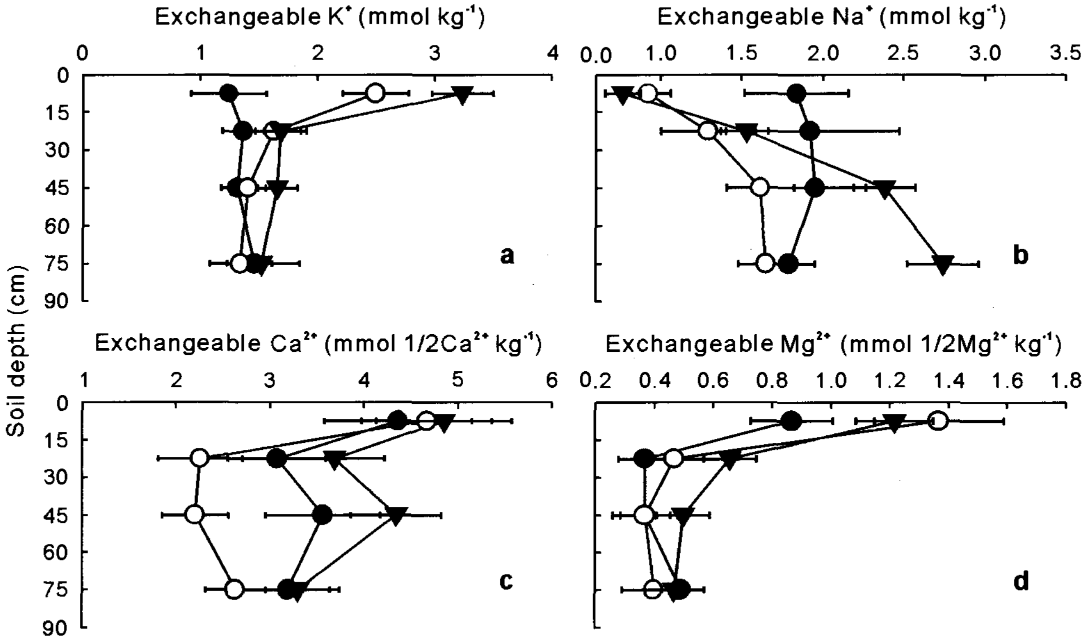

Fig. 3 Vertical distributions of K^+ (a), Na^+ (b), Ca^{2+} (c), and Mg^{2+} (d) for the three successional forests of the Dinghushan Biosphere Reserve (1999–2004): the regional forest community, subtropical monsoon evergreen broad-leaved forest (MEBF); the transitional succession community, coniferous and broad-leaved mixed forest (MF); and the pioneer coniferous Masson pine (*Pinus massoniana*) forest (MPF). Error bar represents one standard deviation.

Ca^{2+} displayed some of the largest variations not only in the soil profile (nonlinear decrease as a function of depth) but also in the course of the forest succession (nonlinear increase as a function of forest succession series). All three forest stands showed the highest exchangeable Ca^{2+} concentrations in the topsoil (Fig. 3c). The average exchangeable Ca^{2+} concentrations for all soil layers (0–90 cm) were 4.5, 4.1, and 5.3 mmol $1/2Ca^{2+}$ kg^{-1} in MPF, MF, and MEBF, respectively. MF had the shallowest exchangeable Ca^{2+} distribution among all three forests. Exchangeable Ca^{2+} was significantly uplifted and enriched in the topsoil layer for all three forests, especially MF. Exchangeable Mg^{2+} concentration also showed no-linear decrease with the soil depth from the surface to the deep layers in each forest (Fig. 3d). The value in the topsoil layer was three to four times more than that in the 60–90 cm layer.

K^+:Na^+ in plants is typically $\gg 1$ and usually higher than that observed in soil (Jobbagy and Jackson, 2004). The maximum value of K^+:Na^+ was found in MEBF topsoil because of obviously enriched K^+ and dispersed Na^+ in this layer. K^+:Na^+ in this layer was about half of that in plants in the same forest reported by Lin *et al.* (1989). MPF and MF had similar results. Ca^{2+} displays some of the largest variations in foliar concentrations and consistent differences among plant functional types, especially compared to other exchangeable cations, such as K^+ (Thompson *et al.*, 1997). Through the values of Ca^{2+}:K^+ in soil, Jobbagy and Jackson (2004) suggested that Ca^{2+} should have a higher cycling intensity compared to other exchangeable cations under broad-leaved forest vegetation than under grassland. Consequently, soil Ca^{2+} distribution is shallower in broad-leaved forests than in grasslands. For these three forests, Ca^{2+}:K^+ values in soil are 3.7, 1.7, and 2.0 for MPF, MF, and MEBF, respectively. The previous study shows that Ca^{2+}:K^+ values in litterfall are 1.59 and 0.72 for MPF and MF, respectively (Weng *et al.*, 1993). Ratios for MPF in soil and litterfall are twice more than those for MF. According to Jobbagy and Jackson (2004), the soil Ca^{2+} distribution should be shallower in MF than in MPF. This speculation is confirmed by the present observation, as shown in Fig. 3c. Mg^{2+} is slightly less mobile and subject to some plant uplift, therefore, its distribution should be shallower. In this study, exchangeable Mg^{2+} was found to be considerably enriched in the topsoil and slightly increased with forest succession.

Relationships among SWC, SOM, and SEC

In all plots of the three forests, SWC, SOM, and SEC were obviously enriched in the topsoil, except for Na^+. In the research by Zhou and Yan (2000), soil clay increases with soil depth. Statistical tests reveal that soil clay had significant influences on SWC, SOM, and SEC (Table II). Martins *et al.* (1991) reported that changes in SOM content and dynamics, which occur after clear felling of tropical rain forests and establishment of crops or pastures, are closely related to changes in soil physical properties. SWC and SOM have long been recognized as important factors affecting the functioning of ecosystems and the succession of their vegetation. They play a very important role in supply of nutrients and carbon balance in forest ecosystems (de Kovel *et al.*, 2000).

TABLE II

Values of t-test[a)] of significant differences among soil clay, water content (SWC), organic matter (SOM), K^+, Na^+, Ca^{2+}, and Mg^{2+} ($n = 12$) in the three successional forests of the Dinghushan Biosphere Reserve

	Clay[b)]	SWC	SOM	K^+	Na^+	Ca^{2+}	Mg^{2+}
Clay	0.000	29.163	28.857	29.102	19.115	27.935	29.775
SWC		0.000	0.802	0.841	1.044	−1.963	2.167
SOM			0.000	−0.739	−0.946	−1.270	1.059
K^+				0.000	0.001	−1.847	1.474
Na^+					0.000	−1.941	1.570
Ca^{2+}						0.000	0.341
Mg^{2+}							0.000

[a)] The critical value of 95% significant level is 2.07.

[b)] The data of soil clay are cited from the database of the Dinghushan Forest Ecosystem Research Station.

On the basis of the measurements of SWC and SOM in different soil layers for all three forests, the following linear regression (Fig. 4) was fitted:

$$\mathrm{SWC} = 2.836 \times \mathrm{SOM} + 130.900 \quad (R^2 = 0.724,\ n = 12,\ P < 0.05)$$

Soil water content explained more that 70% of SOM variation in different soil layers for all three forests. This result was consistent with the studies by Dutartre *et al.* (1993) and Koutika *et al.* (1997). No significant differences were found ($P = 0.05$) among exchangeable cations (Table II). CEC data were compiled by Liu *et al.* (2002a) by determining the extractable cations (K^+, Ca^{2+}, Mg^{2+}, and Na^+) and estimating H^+ and Al^{3+} from soil and buffer pH measurements. SOM is one of the main sources of CEC and higher SOM is usually related to higher CEC. The close relationships between CEC and SOM are shown in Fig. 4 for all three forest stands. CEC was fairly well described by the regression:

$$\mathrm{CEC} = 212 \times (1 - \mathrm{e}^{-0.074\times\mathrm{SOM}}) \quad (R^2 = 0.97,\ n = 12,\ P < 0.05)$$

The above regression showed that SOM explained more than 95% of the total variation in the measured CEC by Liu *et al.* (2002a) for all three forests. Although CEC buffered the fluctuations in nutrient availability and soil pH, its variation can be well explained by SOM in all three forest soils.

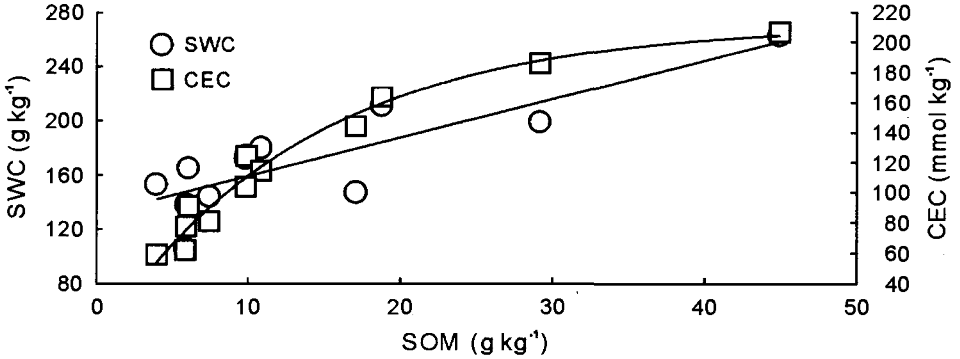

Fig. 4 Relationships of soil water content (SWC) and cation exchange capacity (CEC) with soil organic matter (SOM) in all layers of the three successional forests of the Dinghushan Biosphere Reserve.

Factors determining SOM and SEC

Factors affecting SOM decomposition and accumulation rates include SOM form, soil texture and drainage, C:N ratios of organic materials, climate, and cropping practices. The main factors are regional climate (rainfall and temperature), soil type, vegetative growth, and topography. The primary factors determining SEC were clay and SOM (Table II). The high cation exchange properties of SOM are a major means by which organic matter is able to bind soil particles together to form a stable structure. The reactive regions present in humus are numerous, and provide molecules the capacity to bind to each other and to mineral soil particles, and also to react with cations in the soil solution. For the forest ecosystem, litter input processes constitute an important system to transfer organic matter, exchangeable cations, and energy from the vegetation to the soil (Arunachlam *et al.*, 1998; Liu *et al.*, 2002b). The data (compiled by Zhang *et al.*, 2000) of average annual litterfall productions and their average annual decomposition rates in all three forest ecosystems were analyzed, and the results showed that the SOM in the topsoil layer was positively correlated with the amount of litterfall decomposition (Fig. 5). It was also found that a single exponential function could be used to quite well describe the responses of CEC to litterfall decomposition in the three forests (Fig. 5).

Uplift and increase of SWC, SOM, and CEC with forest succession

At the early stages of subtropical forest succession (MPF), the forest was dominated by needle-leaved tree species, with only a few broad-leaved species. Pioneer species constantly added organic matter and

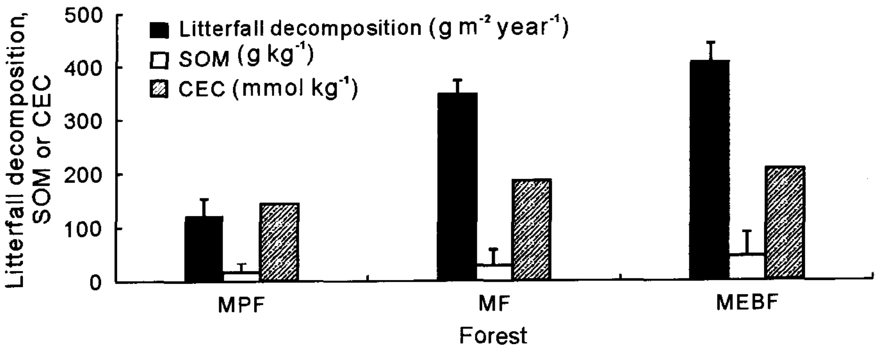

Fig. 5 Annual amount of litterfall decomposition or soil organic matter (SOM) in the topsoil layer or cation exchange capacity (CEC) in the soil of the three successional forests of the Dinghushan Biosphere Reserve: the regional forest community, subtropical monsoon evergreen broad-leaved forest (MEBF); the transitional succession community, coniferous and broad-leaved mixed forest (MF); and the pioneer coniferous Masson pine (*Pinus massoniana*) forest (MPF). Error bar represents one standard deviation.

nitrogen to soil and the ameliorated soil provided a suitable environment for the establishment of broad-leaved species. SWC, SOM, and CEC had been changed slightly (uplift and increase). During succession, the forest was invaded by many broad-leaved species that became the dominating species in MEBF. Broad-leaved species lift up and move SWC, SOM, and CEC on a large scale by their fast growth. The rapid and efficient turnover of organic matter and cycling of nutrients were necessary to sustain the high dry matter production. Plants played a dominant role in controlling SWC, SOM, and CEC distributions in the soil. This finding agreed with the hypothesis of Jobbagy and Jackson (2001) that the nutrients will be enriched in the topsoil when the nutrients become increasingly scarce in the soil. When MF was significantly disturbed and degraded by some factors, such as rapid soil erosion, uplift may favor SWC, SOM, and CEC losses, by exposing larger amounts of them in the topsoil. Reforestation and vegetation rehabilitation would be then more difficult because of lower nutrients in deeper soil layers. With the further development of a broad-leaved overstorey (MEBF), the microhabitat for the survival and regeneration of needle-leaved species was lost, and therefore they were eventually eliminated from the ecosystem.

The Afforesting Wild Hill Program in the subtropical region of South China was set up at the end of the last century, aiming at planting and protecting forests in the wild hills to reduce or alleviate soil erosion and land degradation. According to the research by Zhou and Yan (2000), pioneer forest community MPF have covered most parts of wild hill lands, and developed rapidly through natural and human processes towards MF. On the basis of the succession theory (Peng and Wang, 1995), MF may be a permanent feature of the subtropical landscape in South China. Understanding the changes of SWC, SOM, and CEC during forest succession would be of great help in protecting the dominated forest MF from being disturbed or taken over by MPF.

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