ΦYTON
REVISTA INTERNACIONAL DE BOTÁNICA EXPERIMENTAL
INTERNATIONAL JOURNAL OF EXPERIMENTAL BOTANY
FUNDACION ROMULO RAGGIO
Gaspar Campos 861, 1638 Vicente López (BA), Argentina
www.revistaphyton.fund-romuloraggio.org.ar

The nutrient accumulation pattern and cycling in natural secondary forests in North China. A case study from the Caijiachuan watershed, Shanxi Province

Ciclo y modelo de acumulación de nutrientes en bosques secundarios naturales en el Norte de China. Un caso de estudio de la cuenca Caijiachuan, Shanxi Province

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Abstract. In order to examine the nutrient content, and the distribution and accumulation patterns of individual nutrients in the natural secondary forests (NSFs), sample NSF plots were selected in the Caijiachuan watershed on the Loess Plateau. On the basis of a comprehensive field inventory to the NSFs in Caijiachuan watershed, a 40 m × 40 m sample plot was selected as the representative plot. Each tree plant was then measured to select the standard tree in accordance with a diameter-scale. For measurement of the biomass in the above-ground part of the tree, it was divided into parts and measured. The study measured the concentration of the 5 major macronutrients (namely N, P, K, Ca and Mg) and the 8 major micronutrients (namely Cd, Fe, Mn, Cu, Zn, Pb, Ni and B) in plant organs. An appropriate amount of the samples were weighed and exposed to H_2SO_4-H_2O_2 using the Kjeldahl heating digestion method. While N content was measured with the semi-micro determination method, P content was measured using vanadium molybdate yellow colorimetric method HNO_3-$HClO_4$ ICP heating digestion method was applied to determine the contents of Ca, Mg, K, Na, Fe, Cu, Zn, Mn, B, Cd, Pb, Ni. As for soil samples, corresponding approaches were employed to work out the contents of each of the above-mentioned nutrient elements. Among the tree, shrub and herbaceous layers, the content of macro-nutrients follows the sequence of Ca > N > K > Mg > P, compared with their counterpart of K > N > Ca > P > Mg in the litter layer. For the micronutrient contents, similar sequences (i.e., Fe > Mn > Zn > B > Cu > Pb > Ni > Cd) were observed in the tree, shrub and litter layers; whereas the herbaceous layer demonstrated a different sequence of Fe > Mn > B > Zn > Cu > Pb > Ni > Cd. Within the NSF ecosystem, total accumulation of the 5 major macronutrients (excluding that in the soil) reached 1089.82 kg/ha, of which the tree layer took up the largest share, 40.82%, followed in turn by the shrub layer (31.28%), the herbaceous layer (12.55%) and the litter layer (15.36%). In terms of nutrient-concentration in

Resumen. Con el objetivo de examinar el contenido de nutrientes, y los modelos de distribución y acumulación de nutrientes en los bosques secundarios naturales (NSFs), se muestrearon parcelas en los NSFs en la cuenca Caijiachuan en el Loess Plateau, China. En base a un importante inventario de muestreos a campo en los NSFs en la cuenca Caijiachuan en el Loess Plateau, se determinó como representativa una parcela de 40 x 40 m. Se midió cada planta arbórea para seleccionar el árbol estándar de acuerdo a una escala de diámetros. Para las mediciones de biomasa en la parte aérea del árbol, el mismo se dividió en partes. Se midió la concentración de los 5 macronutrientes más importantes (N P, K, Ca y Mg) y los 8 principales micronutrientes (Cd, Fe, Mn, Cu, Zn, Pb, Ni y B) en los órganos de la planta. Se pesó una cantidad apropiada de muestra y se expuso a ácido sulfúrico-peróxido de hidrógeno usando el método de digestión Kjeldahl. La concentración de N se midió con el método semi-micro Kjeldahl. La concentración de P se midió utilizando un método colorimétrico (molibdato de vanadio), y un después de un método de digestión se determinaron el Ca, Mg, K, Na, Fe, Cu, Zn, Mn, B, Cd, Pb, Ni. Enfoques similares se emplearon para determinar la concentración de nutrientes en las muestras de suelo. Entre los estratos arbóreo, arbustivo y herbáceo, los contenidos de macronutrientes siguieron la secuencia Ca > N > K > Mg > P comparado con K > N > Ca > P > Mg en la broza. Para las concentraciones de los micronutrientes se observaron secuencias similares en los estrato arbóreo, arbustivo y broza: Fe > Mn > Zn > B > Cu > Pb > Ni > Cd. El estrato herbáceo mostró una secuencia diferente: Fe > Mn > B > Zn > Cu > Pb > Ni > Cd. Dentro del ecosistema NSF, la acumulación total de los 5 macronutrientes (excluyendo el suelo) alcanzó 1089.82 kg/ha, de lo cual la mayor parte correspondió a la parte arbórea, 40,82%, seguido por la capa arbustiva, 31,28%, el estrato herbáceo, 12,55%, y la broza (15,36%). En términos de la concentración de nutrientes en los órganos vegetales dentro del árbol, la secuencia fue ramas

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Recibido / Received 8.V.2012. Aceptado / Accepted 12.IV.2013.

the plant organs within the tree layer, the overall sequence can be expressed as branches > roots > wood > bark > leaves. The total accumulation of the 5 major macro-nutrient in the soil reached 634.97 t/ha. In terms of the accumulation coefficients in each of the layers, the general pattern can be summed up as: shrub layer > tree layer > herbaceous layer, and N > P > Ca > K > Mg. In terms of the plant organ accumulation coefficients at the tree layer, the sequence was leaves > branches > roots > bark > wood. As for the accumulation coefficients of the micronutrients, the overall sequences for the tree layer, the shrub layer and the herbaceous layer can be listed as Cd > B > Zn > Cu > Mn > Ni > Pb > Fe; Cd > B > Zn > Mn > Cu > Ni > Pb > Fe and Cd > B > Mn > Zn > Cu > Ni > Pb > Fe, respectively. The study also revealed that the macronutrients that are absorbed, assimilated and returned by the NSF stand annually reached 99.054 kg/(ha·year), 49.155 kg/(ha·year) and 49.899 kg/(ha·year), respectively, demonstrating a well-balanced state of nutrient cycling. With an average of 0.0013, the absorbance index of the macro-nutrients was ranked in the following sequence, N > P > K > Ca > Mg; whereas their utilization and cycling indexes were respectively sequenced as K > P > N > Mg > Ca and K > P > N > Mg > Ca. For the micronutrients the corresponding annual figures were 117.35 g/(ha·year), 50.96 g/(ha·year) and 66.39 g/(ha·year), respectively. The micronutrients, as a whole, showed a relatively small absorbance index (e.g., Cd was the largest=0.0036). The average utilization index of all the microelements was 0.12.

Keywords: Biomass; Biological cycling; Loess Plateau; Microelements; Nutrient elements; China.

> raíces > madera > corteza > hojas. La acumulación total de los 5 macronutrientes en el suelo alcanzó 634.97 t/ha. En términos de los coeficientes de acumulación en cada uno de los estratos, el modelo general fue estrato arbustivo > estrato arbóreo > estrato herbáceo, y N > P, > Ca > K > Mg. En términos de los coeficientes de acumulación de los órganos vegetales en el estrato arbóreo, la secuencia fue hojas > ramas > raíces > corteza > madera. Con respecto a los coeficientes de acumulación de los micronutrientes, las secuencias para los estratos arbóreo, arbustivo y herbáceo fueron Cd > B > Zn > Cu > Mn > Ni > Pb > Fe; Cd > B > Zn > Mn > Cu > Ni > Pb > Fe, y Cd > B > Mn > Zn > Cu > Ni > Pb > Fe, respectivamente. El estudio demostró que los macronutrientes que son absorbidos, asimilados y retornados por el lugar de estudio de NSF alcanzó anualmente 99.054 kg/(ha·año), 49.155 kg/(ha·año) y 49.899 kg/(ha·año), respectivamente, demostrando un buen estado de balance del ciclo de nutrientes. Con un promedio de 0.013, el índice de absorbancia de los macro-nutrientes siguió la siguiente secuencia: N > P > K > Ca > Mg; mientras sus índices de utilización y ciclado fueron respectivamente ordenados en la siguiente forma: K > P > N > Mg > Ca y K > P > N > Mg > Ca. Para los micronutrientes, los datos anuales correspondientes fueron 117,35 g/(ha·año), 50, 96 g/(ha·año) y 66,39 g/(ha·año), respectivamente. Los micronutrientes mostraron un índice de absorbancia relativamente pequeño (ej., Cd fue el mayor: 0.0036). El índice de utilización de todos los microelementos fue 0,12.

Palabras clave: Biomasa; Ciclo biológico; Loess Plateau; Microelementos; Nutrientes; China.

INTRODUCTION

The accumulation and distribution of tree nutrients forms the basis for studying energy and nutrient cycling within forest ecosystems. Bio-cycling of nutrients, one of the major functions of forest ecosystems, is closely related to carbon-cycling; hence, it is of great significance in fields such as restoration-ecology, biodiversity and global climate change. Since the 1970s, notable achievements have been obtained in studies in this field, ranging from earlier research on nutrient accumulation, nutrient distribution and cycling to the more advanced work on seed-configuration based on diagnosing the nutrient-state within tree organs (Tsutuumi et al., 1968; Vitousek, 1982; Sheng et al., 1985; Lisanework & Michelsen, 1994; Smith et al., 1998; Hartemink, 2001; Merino et al., 2008). In China, studies on the productivity and nutrient state of forest ecosystems are mostly focused on plantations in China (Chen & Lin, 1994; Chen et al., 1997; Liu et al., 2002; Ma et al., 2007; Xia et al., 2010). Meanwhile, in-depth studies have also been carried out on the plantations in the hilly regions of the Loess Plateau by Zhao Hubing and Gao Jiarong, mainly on such species as Chinese pine (*Pinus tabulaeformis*) and silver chain (Gao et al., 2002; Liu, 2002; Zhao et al., 2006). Over the last few years, research on the carbon-storage of plants has become the focus of a number of researchers who aim to estimate carbon-storage on the basis of biomass and the corresponding carbon-content indices (Yu, 2003; Shi et al., 2004). Thus, a precise estimate of vegetation carbon-storage is becoming a key component in elaborating the role of vegetation restoration in ensuring a balanced carbon content in terrestrial ecosystems; it is also critical in examining the relationship between global climate change and carbon cycling (Watson, 2000). In the past, extensive research has been carried out on mineral elements, including N, P, K, Ca, Mg and their corresponding physiological functions that are needed for plant growth in terms of mass. In addition, studies have focused on the processes through which such elements become part of the soil, and are then absorbed by plants. The inter-relationships between the five major elements have also been investigated with the conclusion that the optimal results be achieved for plant growth only when an appropriate ratio between them can be reached (Li, 2007). Similar research on trace elements within plants, including their absorbance, transportation within plants, their physiological as well as biochemical functions, their impacts on the growth and quality of plants, and prevention and testing of heavy metal pollution to plants, have also yielded promising results (You et al., 2005).

As a result of the changing water conditions and human-induced impacts, hardly any primitive natural forest still exists in the Loess Plateau region. This has significant negative implications for the formation and functioning of the ecosystems. Compared with plantations, relatively fewer studies have been carried out so far on natural secondary forests (NSFs). As a major secondary source of forest resources, the NSFs are of strategic importance to China's modernization. Therefore, it is of great theoretical as well as practical importance to look into the nutrient cycling within the NSF ecosystems to obtain a better understanding of their characteristics. The study presented here should also shed some new light on ways to improve the management of NSFs in the Loess region and strengthen efforts for their protection.

MATERIALS AND METHODS

Site Description. The study was carried out in the Caijiachuan watershed, Jixian County, Shanxi Province, which falls within the scope of The Chinese National Forestry Ecosystem Observation and Research Station (Jixian, Shanxi). Located at 36° 16′N and 110° 43 E, the site ranges between 1050~1200 m in altitude above sea level, with an annual mean temperature of 10 °C and 172 frost-free-days. While the average annual rainfall is 579.1 mm, with an extreme high of 828.9 mm (in 1956), and an extreme low of 277.7 mm (in 1997), the corresponding annual mean evaporation is as high as 1729 mm (Wei, 2002). The soil belongs to a carbonic acid cinnamon type. The forests covered under the study are mainly NSFs dominated by David poplars (*Populus davidiana*) and East-Liaoning oaks (*Quercus wutaishabcia* Mayr.). With a crown closure of 0.7 and density of 1655 trees/ha, the study forest is composed of trees whose average breast-height-diameter, average height and average age are, respectively, 6.5 cm, 7.5 m and 20 years for poplars, and 5 cm, 5.5 m, 10 years for oaks.

Due to the influences of climate, soil and human activities, the forest coverage within the watershed is estimated to be 72% (Zhang et al., 2005). In addition to the NSFs, large stretches of vigorous-growing Chinese pine (*Pinus tabulae formis*) and silver chain plantations (that developed over the last few decades) can also be found within the study watershed. The major species in the natural forests include *Populus davidiana*, *Quercus wutaishabcia* Mayr, *Ostryopsis davidiana*, *Lespedeza bicolor* Turcz., *Rose Xanthina* Lindl., *Spiraea trilobata* Liudl., *Bothriochloa ischaemum*, *Agropyron cristatum,* as well as *Artemisia capillaries* Thunb., *Artemisia argyi* Lévl. et Vant., and *Artemisia annua* Linn. In terms of stand type (composition and formation), the state of growth and site conditions, and the study forest is representative of those typically found in the Loess Plateau region.

Biomass measurement, tree sample collection and processing. On the basis of a comprehensive field inventory to the NSFs in Caijiachuan watershed, a 40 m×40 m sample plot was selected as representative. Each tree plant (adult tree) was then measured to select the 3 standard tree in accordance with diameter-scale 6-7 cm for *Populus,* 5-6 cm for *Quercus.* For measurement of the biomass in the above-ground part of the tree, the tree was divided into parts and measured. The method of "thorough digging", in which the entire root system is dug out and taken back to the lab, was applied to assess the biomass content of the root system. After washing, the root was wind-dried and sampled. The samples were oven-dried and analyzed to determine the biomass content of the entire root system by proportions. An anatomical approach was used to work out the biomass content for each tree organ. For the shrub and herbaceous layers, a "yielding sampling" method was applied to measure the weight of both the above- and under-ground sections of the plants. Five (5) sub-samples, each 1 m ×1 m in size, were selected within the sample plot to determine the biomass content of the shrub under-story in branches, leaves and roots. Another eight (8) 1 × 1 m sub-samples were chosen to determine the biomass content of the herbaceous plants in both the above- and underground sections. Sample collection was carried out in late August and early September, 2006. Meanwhile, five (5) 0.5 × 0.5 m baskets, together with another 1 × 1 m basket, were randomly placed on the sample plot to collect all the fallen litter, which was in turn used to measure biomass content.

Concurrently when the biomass contents were measured, 3 samples (each 500 grams), respectively, were also taken from the stems (include wood and bark), branches, leaves, flowers, fruits, and roots of the standard plants in both the tree and shrub layers, as well as both the above- and underground sections of the herbaceous layer, to determine their respective nutrient content. Samples were also taken from the fresh litter and the semi-decomposed ground layer. All the samples were oven-dried at 80~90 °C for 30 min on the same day they were collected, and drying continued at a constant temperature of 85 °C until they were completely dry, so that their respective moisture content could be determined.

Soil sample collection and processing. Three (3) intersections were dug out on the sample plot to collect soil samples with the "cutting ring method" to measure bulk density. Six (6) soil samples, each weighing 1 kg, were taken at depths of 0~10 cm, 10~20 cm, 20~40 cm, 40~60 cm, 60~80 cm and 80~100 cm, and then subjected to chemical tests in the lab.

Measurement of nutrient-content of the samples. The plant samples collected in the field were oven-dried at 85 °C, and then ground and put into labeled-bottles. Prior to chemical analysis, the samples were again oven-dried at 105 °C for 1 h. An appropriate amount of the samples was weighed and resolved in H_2SO_4-H_2O_2 resolution with the Kjeldahl heating digestion method. Nitrogen content was measured with the semi-micro determination method, P content with vanadium molybdate yellow colorimetric method HNO_3-$HClO_4$ ICP heating digestion method was applied to determine the contents of Ca, Mg, K, Na, Fe, Cu, Zn, Mn, B, Cd, Pb, Ni. As for soil samples, corresponding approaches were employed to work out the contents of each of the above-mentioned nutrient elements.

RESULTS AND DISCUSSION

Biomass content and distribution in the NSFs. The upper and middle reaches of the Caijiachuan watershed are mainly covered with NSFs that are composed of *Populus davidiana*, *Quercus wutaishabcia* Mayr, *Betula platyphylla* Suk. and *Ostryopsis davidiana*, with *Populus davidiana* as the dominant species. The tree, shrub, herbaceous and litter layers accounted, respectively, for 46.02%, 28.99%, 12.75% and 12.23% of the total biomass. This ratio differs from plantations where the tree layer normally takes up an absolute majority of the total biomass, higher than 90% in most instances. On the unique landscape on the Loess Plateau, the biomass within the tree layer still makes up the largest share, but that in the vigorous-growing shrub layer amounts almost to 1/3 of the total.

Being the dominant species in the tree layer, poplar trees accounted for 16.263 t/ha, or 97.92% of the total biomass in this layer. This figure can be further broken down to 12.976 t/ha, or 79.79%, for the above-ground section and 3.286 t/ha, or 20.21%, for the underground section. For the above-ground section, the biomass in the stem wood reached 7.442 t/ha, or 45.76%; bark to 2.028 t/ha, or 12.48%; branches to 2.974 t/ha, or 18.29%; leaves to 0.532 t/ha, or 0.033%. This showed that the biomass content in each of the tree organs can be sequenced as (stem) wood > roots > branches > (stem) bark > leaves. The biomass content of leaves accounts for 16.2% of that in the roots.

The biomass content of *Quercus wutaishabcia* Mayr. is comparatively less, amounting to 0.346 t/ha with 81.32% found above-ground. As to the biomass content in terms of tree organs, the same sequence as that for poplars was observed.

Among the total of 10.4624 t/ha at the shrub layer, branches, roots and leaves made up 49.16%, 47.24% and 3.6%, respectively, demonstrating a sequence of branch > root > leaves. Compared with plantations, the percentage of biomass at the shrub layer is considerably higher in NSFs, suggesting that the water/soil conservation function of the latter is much more powerful than that of the former. At the herbaceous layer, 17.27% of the total biomass content was found in the above-ground section, and 82.73% in the underground section, with the latter making up an absolute majority, which is consistent with the findings of Zhang et al. (2002).

Nutrient content

Analysis of macroelements. The tree layer constitutes the primary component of the NSF ecosystem, playing the chief role as the productive force, and at the same time as a key player in the material circulation within the ecosystem. Due to the different physiological and biological properties of each tree organ, nutrient distribution in the organs also varies. In poplars for instance, the N, P and Mg content were highest in the leaves, branches and roots, followed in turn by stem bark and stem wood. K was more densely concentrated in the bark than in the branches, with still less in the wood. As for *Quercus wutaishabcia* Mayr., its leaves and branches had the highest N, P and Mg content, followed by bark and roots, with far less in its wood. However, in terms of K-content the sequence can be expressed as leaves > bark > branches > wood > roots. At the same time, the bark showed the highest Ca-content. The obvious higher concentrations of N, P, K and Mg in the leaves of *Quercus wutaishabcia* Mayr., in comparison to its branches and twigs, is consistent with the findings of Huang J.H. & Gao X.M. (1997). The composition of the tree layer, as well as the internal niches of the concerned ecosystem, to a large extent determine biodiversity at the shrub and herbaceous layers. However, nutrient content is generally higher than that of the tree layer, which is probably linked to the faster rate of growth in the shrub and herbaceous layers. Compared with the shrub layer, the nutrient content in each organ in the herbaceous layer varies depending on the specific organ that is concerned. Nevertheless, regardless of the differences between layers and organs, the nutrient content followed a common sequence, Ca > N > K > Mg > P.

Analysis of microelements (Trace elements). At the tree layer, the content of trace elements followed a sequence of Fe > Mn > Zn > B > Cu > Pb > Ni > Cd, with Fe, Mn and Zn relatively higher, and Pb, Ni and Cd lower (Fig.1). This sequence can be explained given that while Fe, Mn and Zn constitute critical elements for the process of photosynthesis, Pb, Ni and Cd are heavy metals that are hazardous to plants. The content of trace elements in each organ was roughly consistent between poplar and *Quercus wutaishabcia* Mayr. While the average content of Fe, Mn, Pb, Ni and B in the latter is higher than that in the former, the reverse was true for such elements of Cu, Zn and Cd. Generally speaking, with the exception of Cu and Ni, noticeable differences existed between organs in terms of trace element concentration. The sequences are listed respectively as follows, Fe, roots > bark > branches > leaves > wood; Mn, leaves > bark > branches > roots > wood; Zn and Cd, bark > roots > branches > leaves > wood; Pb, bark > leaves > branches > roots > wood; B, leaves > bark > roots > branches > wood. The lower content of trace elements in wood than on leaves serve as evidence for the different roles that varying organs play in the growth of the plants. As the respective organs for photosynthesis and translocation of water/nutrients, both the leaves and bark demand larger quantities of nutrients to ensure their vitality for assimilation. Contrarily, wood plays a relatively weaker physiological and biochemical role and therefore need far comparatively less nutrients.

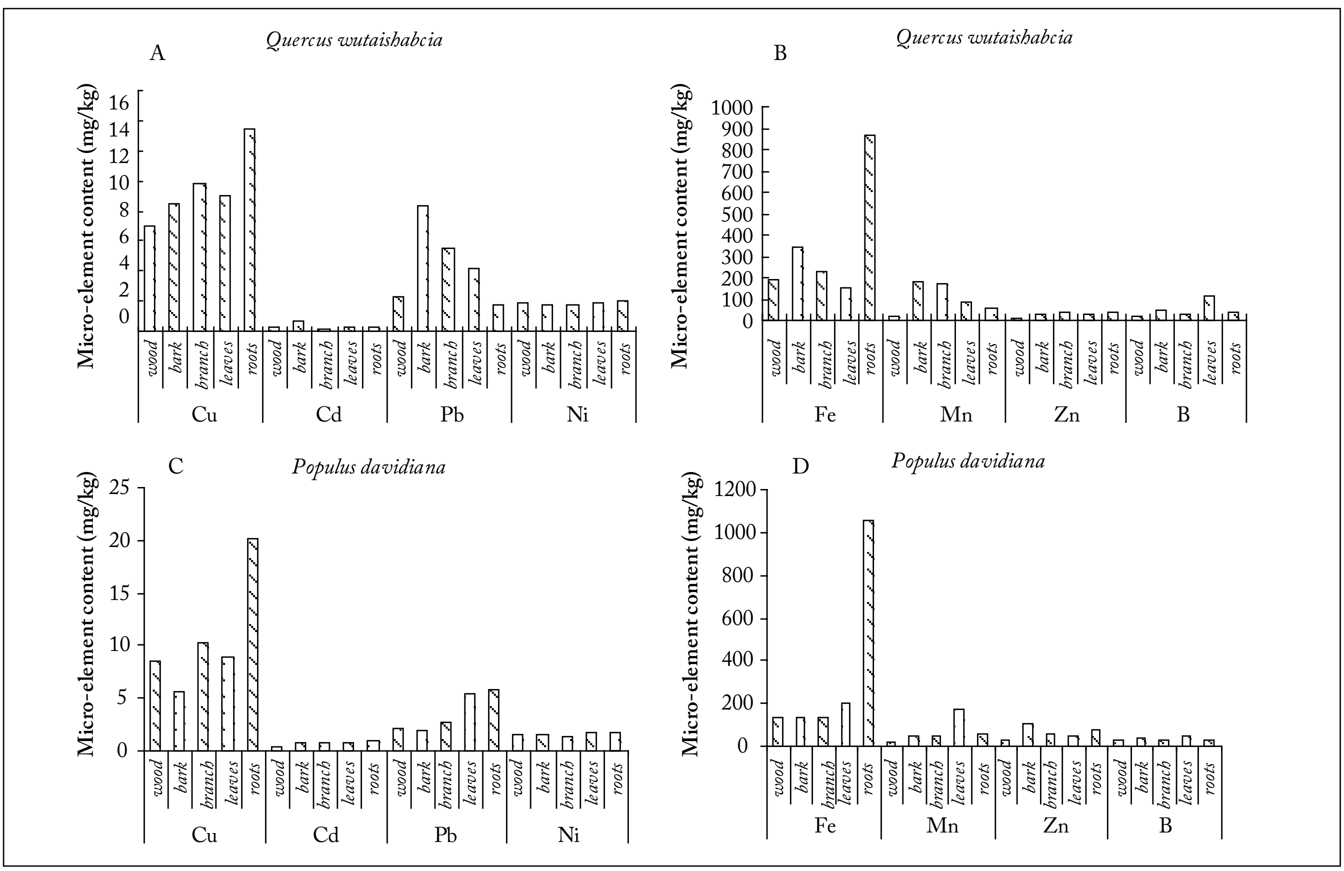

Fig. 1. Microelement content of the different organs in the *Quercus wutaishabcia* and *Populus davidiana*.
Fig. 1. Contenido de microelementos de los diferentes órganos en *Quercus wutaishabcia* y *Populus davidiana.*

According to the LSD multiple comparative analysis of the content of trace element of *Populus davidiana*, there was significant differences between Fe and other elements ($p \leq 0.05$), while the remaining seven kinds of elements did not show differences with each other ($p \geq 0.05$). Taking the LSD multiple comparative analysis for the content of trace element of *Quercus wutaishabcia*, there existed the same law. The small difference is that there was a significant difference between Fe and other elements (sig=0). According to the LSD multiple comparative analysis of the the content of trace element of the shrub layer, except for Mn, there was significant differences between Fe and other elements, and the remaining seven elements did not differ with each other.

Nutrient accumulation and distribution

Accumulation and distribution of macroelements. The accumulation of nutrient elements in NSF ecosystems is derived from multiplying the biomass by the nutrient concentration in each organ, and is therefore determined by both factors, biomass and nutrient concentration. The total accumulation of nutrient elements is the result of the interactive function between the forest community and its corresponding environment.

The accumulation of the 5 major macro-elements reached 1089.82 kg/ha (excluding that in the soil). For the entire forest ecosystem, the tree layer, whose primary productive processes both fix energy and accumulate nutrients, was the most active and most important sub-system, bearing 444.84 kg/ha of nutrients, or 40.82% that of the total NSF ecosystem. The concentration of the nutrient elements in the NSF followed the sequence, Ca > N > K > Mg > P. Although tree woods, when calculated in terms of unit content, had the least rate of nutrient content, they showed the largest amounts of such elements at the tree layer. This suggests that a considerable share of the nutrients is stored in tree trunks. On the contrary, though the leaves had the highest unit content of nutrients, they had the least total accumulation. As for the accumulation in each of the organs, the following order can be observed at the tree layer: branches > roots > wood > bark > leaves. Calcium took up 53.08% and 54.54% of the corresponding total

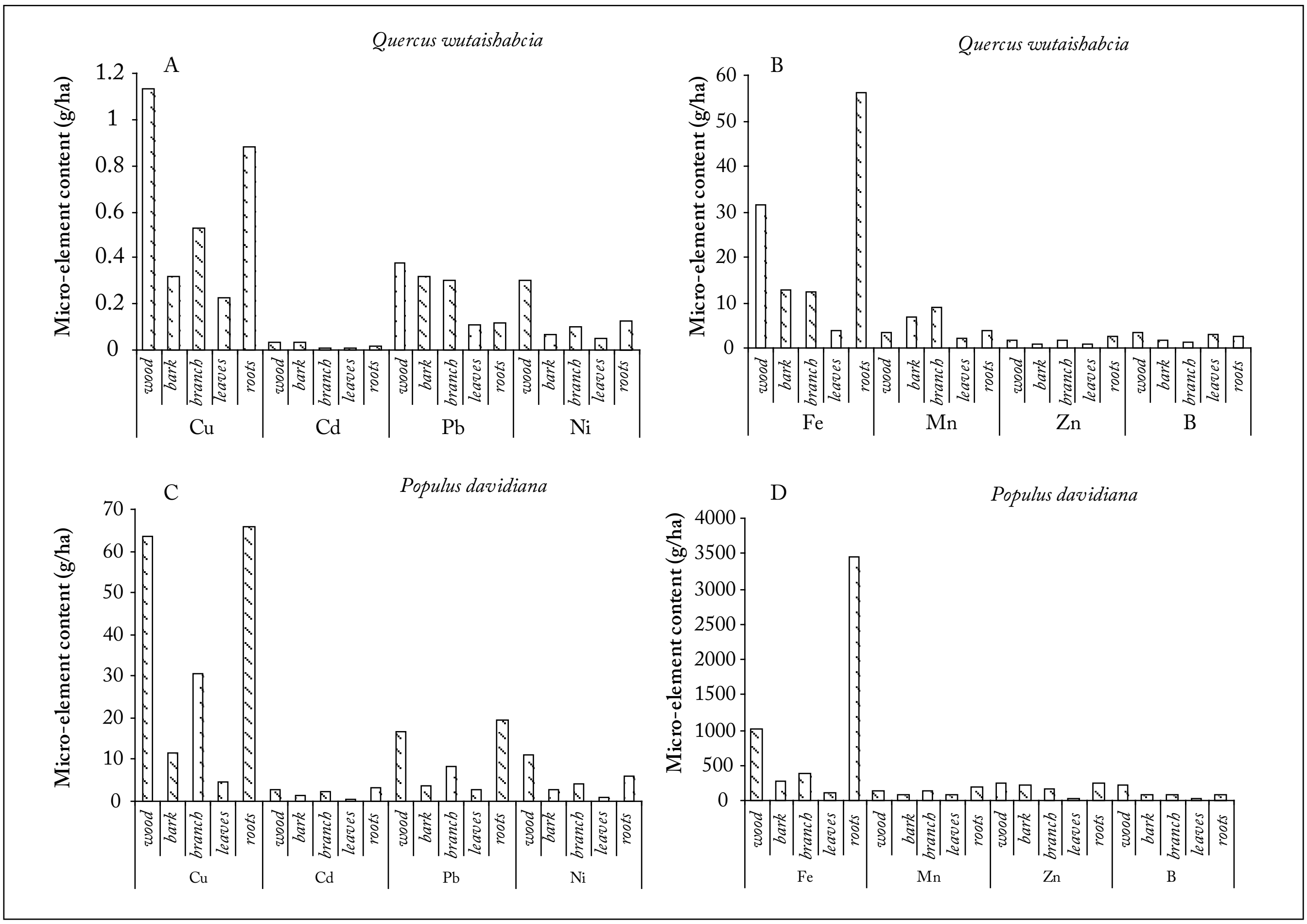

Fig. 2. The microelement accumulation and distribution in different organs of *Quercus wutaishabcia* and *Populus davidiana*.
Fig. 2. Acumulación y distribución de microelementos en diferentes órganos de *Quercus wutaishabcia* y *Populus davidiana.*

nutrient accumulations in the tree and shrub layers, respectively. No significant differences were found between the tree and the shrub layers in their Ca accumulation, both accounting for a fairly high percentage of the total.

Fertility rate is the most fundamental property of soil as well as a key indicator of its quality, projecting a major impact on the evolution of plant communities growing upon it. The state of soil fertility at a particular stage does not only reflect the reciprocal influences between the soil and plant communities in the past, but also determines the baseline conditions and fertility of the soil for the succeeding plant communities. The soil in the NSFs in the Loess region is relatively poor in fertility; however, it has a relatively large proportion of its nutrients concentrated in the underground section (soil) of the ecosystem. Total accumulation of the 5 major nutrient elements in the soil reached 634.97 t/ha, and the accumulation nutrients accounted for 95.32% (N), 99.64% (P), 99.91% (K), 99.84% (Ca) and 99.95% (Mg) of the total amounts. As can be seen, the storage of N was relatively low and may turn out to be a major factor that constraints plant growth.

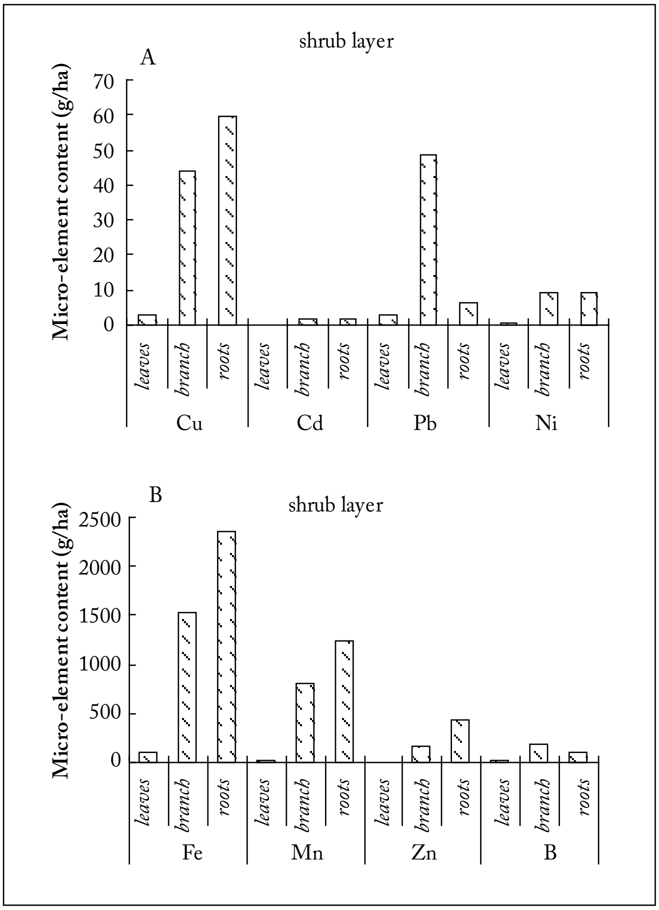

Fig. 3. Microelement accumulation and distribution in different organs of shrub layer.
Fig. 3. Acumulación y distribución de microelementos en diferentes órganos del estrato arbustivo.

Accumulation and distribution of microelements. The total accumulation of microelements in the tree layer reached 7740.84 g/ha, with 7572.81 g/ha for poplars and 168.02 g/ha for *Quercus wutaishabcia* Mayr. Similar sequences of microelement concentration in the organs were found for both species (Fig.2), namely, roots > wood > branches > bark > leaves, with the roots and leaves respectively taking up 53.66% and 3.48% of the total accumulation. When ordered by the specific elements, the sequences were as follows: Fe > Zn > Mn > B > Cu > Pb > Ni > Cd (for poplar); and Fe > Mn > B > Zn > Cu > Pb > Ni > Cd (for *Quercus wutaishabcia* Mayr.). In both cases, Fe had the largest accumulation, accounting for 69.39%, and Cd had the least, accounting for merely 0.13%.

At the shrub layer, total accumulation was 7143.24 g/ha, of which 2.50%, 38.88% and 58.63% were respectively stored in the leaves, branches and roots. In terms of the specific elements, the order can be listed as follows, Fe > Mn > Zn > B > Cu > Pb > Ni > Cd (Fig.3), with Fe accounted for 55.74%, Mn accounted for 28.79%, Cd made up the smallest share of 0.05%, and 10% for the other few elements as a whole.

Characteristics of nutrient accumulation in NSFs. Forest plants chiefly absorb nutrients elements from soil through their roots and then store them within their corresponding organs (Gao et al., 2002). The relationship between the nutrient content in plants and that in the soil tells much about the characteristics of the nutrient-exchange that takes place between the two. Nutrient content in plants is determined by the specific species and their respective organs, but also by the quantity of nutrients that are available in the soil for the plants to absorb them. The correlation between the nutrient content in the plants and that in the soil can be expressed as an accumulation coefficient, which is determined by the plants' desirability for nutrients, the state in which the nutrients exist in the soil, the nutrient content in the soil, as well as by the plants' capacity for storing a particular element. Depending on the species and their respective organs, the accumulation and concentration of each nutrient element may vary in their properties. It was revealed in our research that the accumulation and concentration of nutrients varied in forest stands from layer to layer (Table 1, Table 2). Ranked by layers, the general trend is, shrub layer > tree layer > herbaceous layer. Ranked by the organs of plants belonging to the tree layer, the overall sequence can be summed up as: branches > roots > wood > bark > leaves, N > P > Ca > K > Mg. Being the essential macroelements that are demanded in huge quantities by plants, the concentration coefficient of N and P were notably higher than those of the other elements. Theoretically speaking, the Loess region is rich in Ca content and plants have a relatively higher capacity for storing Ca. Nevertheless, research showed that the concentration coefficient of Ca was not the greatest, which differed from the case of the pine plantations in the same region. This difference can probably be explained by the frequent human-induced cultivations of the plantations that have altered the original fertility of the soil. Although the shrub and herbaceous layers showed less nutrient storage than the tree layer, their rate of nutrient concentration is relatively higher than that of the latter. This is closely related with their geographical location in the Loess region. The overall sequence of trace element concentration in the tree, shrub and herbaceous layers were Cd > B > Zn > Cu > Mn > Ni > Pb > Fe; Cd > B > Zn > Mn > Cu > Ni > Pb > Fe; and Cd > B > Mn > Zn > Cu > Ni > Pb > Fe, respectively.

Table 1. Accumulation coefficients of nutrient element in soil by different organs in different layers.
Tabla 1. Coeficientes de acumulación de nutrientes en el suelo por diferentes órganos en diferentes estratos.

Layer	Organ	Accumulation coefficient				
		N	P	K	Ca	Mg
Tree	Wood	3.966	0.373	0.100	0.152	0.035
	Bark	9.804	0.777	0.234	0.493	0.104
	Branches	15.163	1.240	0.214	0.480	0.121
	Leaves	24.106	2.314	0.606	0.393	0.224
	Roots	11.750	0.958	0.163	0.362	0.103
	Mean	12.958	1.133	0.263	0.376	0.117
Shrub	Leaves	18.006	0.904	0.753	0.414	0.232
	Branches/twigs	8.233	0.506	0.133	0.268	0.043
	Roots	15.122	1.186	0.263	0.503	0.246
	Mean	13.786	0.865	0.383	0.395	0.174
Herbaceous	Above-ground	17.066	0.865	0.488	0.229	0.099
	Under-ground	8.830	0.521	0.160	0.395	0.095
	Mean	12.949	0.694	0.324	0.312	0.097

Table 2. Microelement accumulation coefficients of the different organs in different layers.
Tabla 2. Coeficientes de acumulación de microelementos de los diferentes órganos en diferentes estratos.

Layer	Organ	Accumulation coefficient							
		Fe	Mn	Cu	Zn	Cd	Pb	Ni	B
Tree	Wood	0.006	0.029	0.130	0.139	3.015	0.020	0.057	0.313
	Bark	0.008	0.161	0.119	0.418	6.750	0.045	0.055	0.545
	Branches	0.006	0.152	0.169	0.294	4.685	0.036	0.055	0.359
	Leaves	0.006	0.183	0.150	0.243	4.670	0.043	0.063	1.025
	Roots	0.033	0.086	0.282	0.358	6.240	0.034	0.066	0.428
	Mean	0.012	0.122	0.170	0.290	5.070	0.036	0.059	0.534
Shrub	Leaves	0.010	0.115	0.130	0.147	4.330	0.066	0.059	0.850
	Twigs	0.010	0.221	0.144	0.206	3.540	0.083	0.062	0.453
	Roots	0.016	0.354	0.202	0.551	3.620	0.012	0.066	0.258
	Mean	0.012	0.230	0.159	0.301	3.830	0.053	0.062	0.520
Herbaceous	Above-ground								
	0.024	0.149	0.151	0.239	6.080	0.069	0.098	0.579	
	Under-ground								
	0.074	0.272	0.170	0.165	2.970	0.033	0.163	0.331	
	Mean	0.049	0.211	0.160	0.202	4.520	0.051	0.131	0.455

Bio-cycling of nutrients in NSFs. Bio-cycling refers to the process through which the nutrient elements circulate between the soil and the plants, covering 3 ecological phases that maintain a balanced ecosystem, intake, storage and return. The characteristics of nutrient bio-cycling are normally shown by absorbance index, utilization index and cycling index. Absorbance index refers to the ratio between the quantity of a given element that is taken in by a given size of plants within a given period of time, and the total quantity of the concerned elements stored in the soil. This index is dependent on the storage of the particular element in the soil as well as the demand of the plants for it. Utilization index refers to the ratio between the quantity of a given element that is taken in by a given size of plants within a given period of time, and the total current amount of the concerned element available in the plants, reflecting the dynamic pace of changes in the storage of a particular element within the ecosystem (Zhang et al., 2006). The intake quantity is the sum of the quantity that is stored in plants and that is returned to the soil. Cycling index refers to the ratio between the quantity of nutrients returned to the soil and that assimilated at a given size of plants at a given period of time, reflecting the quantity of nutrients that are captured and stored in plants during the circulation. This index stands for the intensity of nutrient cycling: the higher it is, and the faster the circulation is, implying that less of the soil's nutrient stock is consumed by plant growth.

The total quantity of macroelements absorbed annually by the NSFs in the region covered by the present study reached 99.054 kg/ha/year (Table 3), with 49.155 kg/ha/year captured and 49.899 kg/ha/year returned. The annual returned quantity was 50.38% of the entire intake, suggesting a balanced nutrient circulation within the ecosystem. The mean absorbance index of the nutrients, sequenced as N > P > K > Ca > Mg, fall at 0.0013, compared with 0.003 for pine plantations in the hilly Loess regions. Judged in terms of utilization index, the major macroelements followed the sequence K > P > N > Mg > Ca, with K ranking highest, indicating the fastest pace of storage. When referring to cycling index, the same sequence (K > P > N > Mg > Ca) applies, suggesting that K had the highest utilization rate as well as the fastest circulation. Ca came last on the list in terms of cycling index, a mere 12.2% that of K.

The annual intake of microelements of the NSFs in the subject region (Jixian County, Shanxi) was 117.35 g/ha/year (Table 4), with 50.96 g/ha/year captured and 66.39 g/ha/year returned. This translated into a 56.57% returned rate of all the nutrients absorbed. Taken as a whole, the trace elements had a smaller absorbance index, with the largest being 0.0036 for Cd, implying a rich content of the concerned elements in the soil. The mean utilization index of these elements was 0.12, with Fe bearing the highest, followed by Ni and B. No significant difference was observed

Table 3. Biologic cycling of macroelements.
Tabla 3. Ciclo biológico de macroelementos.

Item	N	P	K	Ca	Mg	Sum
Absorbed (kg/ha/year)	22.716	3.812	39.103	29.974	3.446	99.054
Returned (kg/ha/year)	10.543	2.638	33.071	3.100	0.547	49.899
Captured (kg/ha/year)	12.173	1.174	6.032	26.874	2.899	49.155
Absorbance index	0.00475	0.00095	0.00041	0.00013	0.00005	0.0013
Utilization index	0.100	0.185	0.325	0.060	0.064	0.147
Cycling index	0.464	0.692	0.846	0.103	0.159	0.453

Table 4. Biologic cycling of microelements.
Tabla 4. Ciclo biológico de microelementos.

Item	Fe	Mn	Cu	Zn	Cd	Pb	Ni	B
Absorbed (g/ha/year)	3245.06	391.07	33.80	169.97	1.70	13.45	8.10	117.35
Returned (g/ha/year)	2636.19	216.75	15.26	71.12	0.80	6.52	5.20	66.39
Captured (g/ha/year)	608.88	174.31	18.54	98.85	0.90	6.94	2.90	50.96
Absorbance index	0.00002	0.00010	0.00011	0.00024	0.00356	0.00005	0.00005	0.00028
Utilization index	0.1786	0.1102	0.1019	0.1032	0.1084	0.1032	0.1235	0.1229
Cycling index	0.812	0.554	0.452	0.418	0.471	0.484	0.642	0.566

in the corresponding figures for the other few elements in this category. The sequence of the cycling indices was Fe > Ni > B > Mn > Pb > Cd > Cu > Zn, with the largest measure of 0.812 for Fe, and the lowest of 0.418 for Zn. With the exception of Fe, there was no significant differences in the cycling indices of the other trace elements, all being higher than 0.4. The relatively larger cycling indices for each of the trace elements are conducive to the buildup of nutrients in the soil and hence improve soil quality.

To sum up briefly, the macro-elements showed a larger absorbance index, but a smaller cycling index than the micro-elements. Meanwhile, there were no significant differences between the utilization indices between the two groups.

CONCLUSIONS

The present study, which focused on the distribution and properties of biomass and nutrient contents of the NSFs in the Loess region, showed that the total biomass thereof reached 36.087 t/ha, declining in their corresponding proportions by layers (tree > shrub > herbaceous > litter). At the tree layer, the biomass content in each of the plant organs followed a sequence of wood > root > branch > bark > leaves. Within the entire NSF ecosystem, the total amount of the 5 major nutrient elements was estimated to be 1089.82 kg/ha (not including the soil layer), with the tree layer, the shrub layer, the herbaceous layer and the litter layer accounting for 40.82%, 31.28%, 12.55% and 15.36%, respectively. However, only average trees were taken for the tree layer calculations in this study. We acknowledge that differences among diameter class/ages may be significant.

Viewed from the total nutrient accumulation in the NSFs in the Loess region, soil still constitutes the primary nutrient bank of the ecosystem. This conclusion coincides with that on *Pinus tabulaeformis* (Zhang et al., 2006).

Viewed from the concentration index of nutrients in each layer, the general trend can be summed up as shrub layer > tree layer > herbaceous layer. In terms of the variation between the plant organs at the tree layer, the concentration followed the sequence of branches > roots > wood > bark > leaves, N > P > Ca > K > Mg. With the rich Ca content in the Loess region, and higher capacity of plants for nutrient absorbance, the storage of Ca in the ecosystem was higher than that of the other elements.

While the absorbance index of the macroelements was larger than that of the trace elements, there was not much difference between the corresponding figures for the utilization indices. The larger cycling index of the trace elements, compared with that of the macroelements, is conducive to nutrient-accumulation in the soil and hence beneficial for improving soil quality.

The total biomass content of the NSF ecosystem was not large, a characteristic closely related with the poor vitality of plants induced by the insufficient rainfalls in the region. Consequently, more attention should be given to water conservation. Annual leaves naturally tended to have a lower nutrient accumulation. This bears similarities to the findings yielded from a study on birch NSFs (Mu et al., 2004). The plants in the shrub layer demonstrated relatively higher vigor. We suggest that timely and regular cultivations are needed in the overly dense stands with the aim of allowing better sunlight penetration. This will be conducive to better growth and improved productivity of the understory plants, hence contributing to more efficient nutrient cycling in the NSF ecosystems, and to a better water and soil conservation.

ACKNOWLEDGEMENTS

This study was supported by CFERN & GENE Award Funds on Ecological Paper, the National Key Technology R&D Program of China (No.2011BA38B06), the Chinese National Forestry Ecosystem Observation and Research Station (Jixian, Shanxi Province, CNRN) project (2005DKA10300) and the Fundamental Research Funds from the Central Universities (BLJD200909).

We thank the other members of our ecosystem station for helping in the research. The authors thank the reviewers and editors for their efforts and time.

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