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Effect of human activities on forest ecosystems: N cycle and soil fertility

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Abstract

Forests are important terrestrial ecosystems, with particular nutrient cycling mechanisms to maintain structure and functions. Nitrogen is essential for forest growth and development, and commonly limited for the forest productivity. N cycles in forest ecosystems are frequently disturbed by intensive human activities. Based on a variety of research results, some potentially important human disturbances are discussed and their effects on forest ecosystems are reviewed. Precipitation is a considerable N input to forest ecosystems. However acid precipitation is detrimental to the ecosystems in the long run. Acidification causes remarkable reduction in forest productivity in the world, due to the harmful effect of acid on plant physiology and more importantly to the reduction in soil fertility by lowering mineralization and increasing N loss by runoff and leaching. The most important nutrient cycling mechanism in forest ecosystems is litterfall. Removal of trunks only for commercial use will not affect N cycle in forest ecosystems significantly, but attention on the intensity and rotation times of harvest should be paid. Clear-cutting should be prevented in forest harvesting. It deserves more attention that the change of environment after clear-cutting will affect the N cycling processes in forest ecosystems, which substantially influence soil fertility and forest productivity. Ammonification and nitrification processes are stimulated after harvesting, by which N is becoming more moveable. Unfortunately in the situation of no assimilation after clear-cutting, much of N will be lost out of the ecosystems and soil fertility will be diminished. The N pool in forest floor and underlying mineral soil is big, but forest productivity is generally low in natural conditions. Forest management is needed to meet the increasing demand for forest products. Optimization of stands structure is the most economic way to increase soil fertility and forest productivity. Mixed coniferous-broad leaved forest is recommended for plantation practice. Addition of fertilizer N effectively promotes forest productivity and may compensate for the N loss from the systems by harvesting.

Introduction

Forests are important terrestrial ecosystems, covering about 1/3 of the land area on earth. A forest ecosystem maintains its structure and functions sustainablely by its particular nutrient cycling mechanisms. Nitrogen is an essential element for forest growth, and usually acts as a limiting nutrient for the productivity of forest ecosystem. Figure 1 shows the principal processes of the forest N cycle.

It is estimated that within a forest rotation 95% of the total N recycles within the ecosystem and external fluxes represent only 5% (Bormann and Likens, 1981). In natural conditions, N is generally accumulated in a forest ecosystem, which means that the balance of the N input to the system minus the output is positive until an equilibrium is attained. The process of N uptake by vegetation and returns to soil as litter periodically is one of the basic features of a forest ecosystem. More than 90% of the soil N reserves are in the soil organic pool, as a potential source of soil available N through mineralization (Cheng et al., 1987; Xu et al., 1995a). Litterfall is the major contribution of soil organic matter in a forest ecosystem. Inorganic N is the most mobile pool in a forest ecosystem, but plays a decisive role in the forest production and the stability of the system. The fact that forest productivity is generally low in natural ecosystem could be considered as an indication of need of forest management.

Fundamentally, forest production is determined by the soil fertility. The biological processes happening in a forest soil are changed by human activities to a

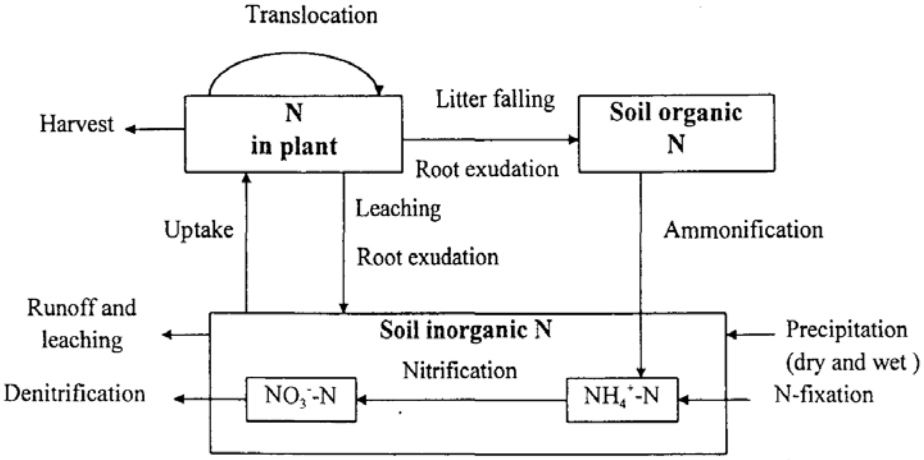

Figure 1. Diagram of N cycle in a forest ecosystem.

great extent. Broadly speaking, tree growth may be considered the end product of a chain of processes both within the tree itself and in the ecosystem at large. The aim of this paper is to review the effects of human disturbance, including industrial emissions, on the N cycle of forest ecosystems in China.

Precipitation acidity and forest productivity

The pH of unpolluted rain is generally given as 5.6 (approximate pH of mineral-free water in equilibrium with atmosphere CO_2). However, human activities contribute significantly to precipitation acidity by producing large amount of air pollutants in the form of strong acid. Area influenced by acid rain is defined as that where at least 50% of the annual precipitation is below pH 5.6. Based on above criteria, acid rain covered about 650,000 km^2 in 1983, corresponding to 6.8% of the land area in China (Zhang and Zhao, 1989). In southern and coastal areas of China the area affected is estimated to be 20,000 km^2 and the annual loss of timber is 1.49 M m^3 (Cheng et al., 1993).

N input through precipitation

N in precipitation is one of the important nutrient sources for a forest ecosystem. In most regions of the world the N content of precipitation is in the range of 2.25 to 11.25 kg ha^{-1} (Cooke, 1967). Annual mean N input through precipitation is estimated to be about 6 kg ha^{-1} based on measurements at a series of locations in the temperate areas of China (Xu, 1987). Both stemflow and throughfall contribute to the N input through precipitation, throughfall representing the major contribution. When precipitation passes through the forest canopy, the N concentration in throughfall is normally increased by the washing of dry deposited N from leaves. The concentration of NH_4^+-N is commonly several times greater than that of NO_3^--N in unpolluted precipitation. Acidification of precipitation is mainly caused by S and N containing acids, and the ion ratio of SO_4^{2-} to NO_3^- in acid rain is characterized to be about 4:1 in China. Thus the NO_3^- concentration in acid-polluted precipitation is increased. The records of N in precipitation at different locations in China are summarized in Table 1, and the leaching coefficients (ratio of N in throughfall to N in precipitation) of various forest types are calculated. Higher N contents in precipitation are found where human activities are intensive, such as in industrial and urban areas. For example, Table 1 shows a high N content in precipitation at Xiashu, Jiangshu Province, which is one of the most active economic regions in China. N from precipitation is effectively assimilated by the forest because of its solubility and because precipitation frequently occurs during the growing season of the trees. A portion of the N in soil and precipitation, especially NO_3^-, will be lost through runoff and leaching when precipitation occurs, but generally N from precipitation is accumulated in a forest ecosystem.

Effect of acid precipitation on forest productivity

Forest productivity is thought to have been decreased by acid precipitation over extensive areas of Europe and eastern North America. It is reported that half of the forest in Poland shows slow growth caused by acid precipitation, and forest growth in southern Sweden was reduced by 2–7%(mean 4%) in the period of 1950–1960 (Zhang and Zhao, 1989). In China the

Table 1. Comparison of N input through precipitation in forests at different locations (kgN ha^{-1} a^{-1})

Location	Forest type	Precipitation	Throughfall	Leaching coefficient
Changbai	Spruce-fir	6.46	8.40	1.30 (Zhang et al., 1995)
Mountain (Jilin)	Korean pine-spruce-fir	7.68	10.96	1.43 (Cheng et al., 1993)
	Korean pine-broad leaved	10.60	13.57	1.28 (Xu et al., 1995a)
Huitong (Hunan)	Chinese fir	7.35	9.78	1.33 (Chen & Pan, 1994)
Xiashu (Jiangshu)	Oak	15.4	24.20	1.57 (Run et al., 1994)
	Chinese fir	15.4	19.20	1.25 (Run et al., 1994)
	Loblolly pine	15.4	17.60	1.14 (Run et al., 1994)

Table 2. Effect of acid rain on the reduction of annual forest growth (%) (Zhang et al., 1993)

Site	Forest type	Growth in DBH*	Growth in height
Guizhou	Masson's pine	6.7	2.0
	Chinese fir	8.5	8.4
Sichuan	Masson's pine	15.1	17.6
	Chinese fir	14.7	14.9

*DBH=diameter at breast height.

reductions of forest growth caused by acid rain are mainly observed in Guizhou and Sichuan Provinces (Table 2). Results of field investigations and simulation experiments showed that the rain which is more acid than pH 4.5 could harm photosynthetic organs, so pH 4.5 is considered as the critical point in the effect of acid on forest growth. The reduction of forest productivity is more significant where pH in precipitation is below 4.5 (Table 3).

Acid deposition may adversely affect tree growth by direct contact through (1) foliage damage, (2) effect on reproductive processes, seeding emergence and early growth, and (3) tree crown interception and leaching (Morrison, 1984). Forest ecosystems may have a certain level of resistance to the external disturbance so that, in some circumstances, tree growth may seem little diminished at present. However, conditions for growth or biological processes are being altered in such a way that, in the future, forest growth will be affected. A potentially important mechanism is that acid deposition affects the forest soil processes which will ultimately affect forest growth.

Acid deposition also has a negative effect on forest productivity both directly, through causing a more acid reaction, and indirectly through leaching of the mineral constituents. Acidification of soil is a natural process, caused by the formation of inorganic and organic acids through microbial activities, and by loss of soil bases through ion exchange and leaching with naturally acid (pH 5.6) rain. Acid precipitation promotes the process of soil acidification and thus could adversely affect soil biota and biotic processes in the forest floor and the underlying mineral soil. Investigations in southwestern China showed that microbial population, which was estimated based on the indoor medium cultivation-petri dish counting method, in the soil of acid rain regions ($pH<4.5$) decreased to 7.2–36.5% of control regions ($pH>4.5$). Microbial activities in soil, such as N-fixation and mineralization, were decreased as well. A significant reduction in ammonification when pH in precipitation is below 4.5 indicates that the capacity of soil to supply mineral N for forest growth is reduced (Table 4). The internal proton production during nitrification that dominates acidification process, is clearly responsible for the adsorbed cation losses. Soil base saturation will be reduced by acid rain, leading to leaching of desorbed cations out of the soil. The base saturation in top soil when exposed to simulated acid rain of pH 2.0 decreased by 65.7% compared with that treated with natural water (pH 6.5) (Liao and Chen, 1991). Higher levels of H^+ effectively exchange NH_4^+ adsorbed to the soil clay to increase the N loss through runoff and leaching. Consequently, it was found that NH_4^+ and NO_3^- contents in the soil were decreased by 27–51% and 2–4% respectively compared with the control soil in this study (Chen et al., 1989). In addition, Al^{3+} that is harmful to fine root growth is activated due

Table 3. Effect of acid rain on the productivity of Masson's pine forest (Chen et al., 1989)

pH in precipitation	Annual mean growth in DBH (cm)	Annual mean growth growth in height (m)	Net production ($Kg\ a^{-1}\ plant^{-1}$)
pH<4.5	0.42	0.38	0.27
pH>4.5	0.69	0.69	0.62
Reduction when pH<4.5 (%)	39.13	44.93	56.45

Table 4. Effect of pH on soil mineralization in Masson's pine forest (Chen et al., 1989)

Date	pH range	Ammonification mg NH_3 g^{-1} soil	Nitrification mg NO_3^- g^{-1} soil
April, 1985	pH<4.5	0.24	11.30
	pH>4.5	0.33	11.54
June, 1985	pH<4.5	0.68	17.22
	pH>4.5	1.40	17.94

to serious soil acidification, which is blamed for the dieback of spruce in Europe. Over the long run, root uptake capacity and soil fertility are diminished due to acid precipitation. It is plausible that acid rain could influence forest growth and productivity by such a mechanism.

Forest harvest and its influence to soil fertility

A recurrent concern at the ecosystem level is that nutrient removal through harvesting will deplete the nutrient capital of the site and hence reduce subsequent production. The concern is increased by the development of whole-tree harvesting and by reduction in the length of rotation time. Special attention has been paid to the effects of short rotation, intensive harvesting practice on N availability, and to the effect of clearcutting on stream water quality.

Loss of N through harvest

Nitrogen concentration in foliage can be 10 to 25 times higher than in trunks. For example, in Korean pine-broad forest of Changbai Mountain, concentrations of nitrogen in Korean pine needle, branch and trunk are 16.30, 4.50 and 0.84 g Kg^{-1}, respectively (Cheng et al., 1987). Trunks are the most commercially useful part of a forest, constituting about 50% of the forest biomass, but less than 20% of the N (Table 5). Removal of trunks only in forest harvesting will not lead to a great loss of N from the ecosystems, and this loss can be recovered by accumulation of N in the following period. However, in the traditional Chinese logging system the residues such as needles, twigs and branches after final cutting are burnt to facilitate the reforestation in the following rotation. Large amounts of N are lost due to burning, as occurs in Chinese fir plantations, and this also affects soil organic matter accumulation. Harvest intensity and rotation time deserve careful attention. If the rotation time is too short to allow the ecosystem to recover the N loss, it will lead to a general decline due to nutrient shortage (Bormann and Likens, 1981). Whole-tree harvest should be avoided, because it makes nutrient loss more seriously, and a longer time will be required for the nutrient level to recover.

Importance of forest litter to soil fertility

Litter fall plays a particular role in the N cycle of a forest ecosystem, by which large amount of N assimilated by vegetation returns to the soil for recycling and subsequent uptake by plants. Foliage is the major component and constitutes 63.5% of the total amount of litter in Korean pine-broad leaves forest of Changbai Mountains (Cheng et al., 1987). The N content in broad leaves is about 1.5 times higher than in Korean pine needles. It has been reported that return of N through litter in broad-leaved forest is about twice as much as in conifers at similar climate conditions. There are also results showing that N content per ha in the litters of a pine forest is only 57.5% of that in a broad-leaved forest nearby. Due to the contribution of broadleaves, in Changbai Mountain, Korean pine-broad leaved forest floor receives 60–70% of assimilated N annually through litter fall while Korean pine-spruce-fir forest receives 20–30%. Broad leaves are easier to decompose than needles due to lower C/N

Table 5. Percentages of biomass and nutrient in organs of different forests (%) (Run et al., 1994)

Forest type	Organ	Biomass	N	P	K	Ca	Mg
Chinese fir	Trunk	48.5	14.5	9.2	11.8	18.6	13.9
	Needle	11.9	37.7	35.8	33.5	28.0	28.3
Loblolly pine	Trunk	48.6	17.5	19.4	18.6	26.0	25.6
	Needle	11.4	33.4	26.5	17.1	19.3	20.7
	Branch	17.1	25.7	24.7	24.1	9.4	17.4
Oak	Trunk	52.3	26.8	34.6	40.6	28.4	39.7
	Branch and leaf	16.6	28.8	31.0	24.8	23.8	21.3

ratio. In this study, annual decay ratios are reported to be 0.694% and 0.257% for leaves and needles, respectively. Mixed Korean pine-broad leaved forest is the major component of the temperate forest in China, constituting 42% (2.2 million ha) of the forest areas in the Northeast (Xu et al., 1995a, b). The mechanism of low retention and high return of nutrient is a reasonable explanation of this ecosystem developing to climax.

Nutrient return through fine root turnover is often ignored, though it is probably significant and deserves further investigation. The results from a case study showed that the annual biomass of dead fine root amounts to 36.8% and 65.9% of that of above-ground litter fall in a plantation of pure Chinese fir and in a mixed plantation of Chinese fir with *Michelia macclurei* Dandy var. *sublanea* Dandy, respectively (Liao et al., 1995). The annual returns of potassium and magnesium through the fine root decomposition exceed the amount through the decomposition of the above-ground litter (Liao et al., 1998).

Impacts of harvest on soil processes and fertility

The impacts of harvest on forest ecosystem are various, and may be summarized as (1) exposing soil to sun light, (2) changing water thermal environment in soil, (3) destroying soil structure, (4) causing loss and water, (5) changing soil biological characteristics. Some harvesting practices, such as whole tree logging, slashing and burning, intensify the above impacts.

Nitrification rates in forest soil are normally low because of the inhibition of nitrifiers by acidity and living plants (Bormann and Likens, 1981). This is an important mechanism for retaining N in a forest ecosystem because most N in form of NH_4^+ adsorbs to soil clay, preventing N loss through runoff and leaching.

If canopy cover decreases, for example due to harvesting, then greater heat and water fluxes reach the soil. This has important consequences for soil organic matter turnover, resulting in an increase in organic matter decomposition and consequent enhanced mineralization in response to canopy thinning, If the system is not N saturated, soil warming leads to increased soil content of NH_4^+. In this situation plant roots will compete efficiently with nitrifying bacteria, resulting in increased root uptake and tree growth, but low NO_3^- content in the soil. This process will result in recovery of the canopy structure. On the other hand, when soil N is becoming saturated due to intensive harvesting, nitrification will be accelerated. Protons are produced in nitrification process, which can effectively substitute the cations (NH_4^+, Al^{3+}, Ca^{2+}, etc.) adsorbed to soil clay into soil solution. In strongly nitrifying soils, root damage is expected to occur through aluminum toxicity to the roots (Morrison, 1984). Since damaged roots lead to a reduction in canopy cover, an acceleration of this feedback stimulation occurs, and the forest has little chance of recovery.

Removing vegetation from large area clearcutting should be prevented. The change of environment after clearcutting significantly affects the N cycle in a forest floor and mineral soil. Without canopy protection, devegetated soil receives direct solar radiation, making soil temperature abnormally high. Without transpiration by plants, soil becomes wetter (Aber et al., 1983). Therefore decomposition processes are stimulated immediately after harvesting, making soil N more moveable. In Hubbard Brook (U.S.), a test of clearcutting on the change of NO_3^- contents in rivers was carried out. The results showed that in the first

Table 6. Major N processes of biological cycles in different forest stands of Changbai Mountain (kgN ha^{-1} a^{-1}) (Xu et al., 1995a, b)

Process	Korean pine-broad leaved	Korean pine-spruce-fir
Uptake	94.9	125.7
Retention	33.2	82.8
Return	61.7	42.9

year NO_3^- contents in rivers was carried out. The results showed that the first year NO_3^- contents in the river were 0.7 and 38.4 mg l^{-1} in control and the devegetated areas, and in the next year the NO_3^- contents changed to 1.3 and 52 mg l^{-1}, respectively (Bormann and Likens, 1981). Thus a great loss of N and other nutrients can be expected when nitrification is stimulated by clearcutting. Denitrification causes N loss from the ecosystem through the reduction of NO_3^- to N_2O and N_2. N_2O is a greenhouse gas.

Forest management

The response of the N cycle in a forest ecosystem to various aspects of forest management is, to a large extent, determined by the capacity of the litter and soil to retain or release N. Forest management practices are normally designed to increase forest production. In similar stand environments, the productivity of a Korean pine plantation is much higher than that of a natural stand (Cheng et al., 1987). Nutrient depletion in managed forest ecosystems has become an important cause for concern. Optimization of stand structure and fertilization is emphasized to meet such challenge.

Stand structure

Forest floor and mineral soil contain large reserves of nutrient, but only a small portion of it participates in the cycling processes. Availability of the N in a forest ecosystem is determined by the rates of decomposition and mineralization. Broad-leaves have higher N concentrations and are easier to be mineralized than needles. Studies in the Changbai Mountain area show that returns of N through mineralization of litter-fall in a broad-leaved forest is twice that in a conifer at similar environment (Table 6). Due to the contribution of broad-leaves, a mixed forest shows higher potential than a conifer to supply N for the forest growth. Moreover, Korean pine-broad leaved forest shows higher capacity to reduce the N loss by leaching (Table 6).

Forest productivity can be increased by optimizing stand structure. A well-designed plantation mixed with coniferous and broad-leaved tree species has better performance in maintaining soil fertility and increasing biomass production. Pure Chinese fir plantations, especially in the case of consecutive rotations, yields less compared with the mixture with *Michelia macclurei* var. *sublanea* because of its greater uptake and smaller return of nutrients. However, the mixture of the above two species returns more N with the ratio of return to uptake 0.17 compared to 0.10 for the pure plantation (Table 7). Other nutrients are also returned more in the mixed plantation (Liao et al., 1995). Furthermore there is increasing evidence that the nutrient release of Chinese fir litter can be enhanced when it decomposes in the presence of certain broad-leaved litter (Feng et al., 1988; Briones and Ineson, 1996; Liao, Ineson and Yang, 1997). Fine root turnover, which was estimated by using the maximum-minimum method, is higher in the mixed plantation: 1.40 compared with 1.29 in the pure plantation of Chinese fir (Table 7).

A possible approach to minimise nutrient deficiency is to mix other tree species in a commercial plantation. Mixed coniferous-broadleaved forests are recommended for forest plantation practices because of the advantages of their N cycling characteristics. However, the total amount of N required for forest production suggests the need for a different strategy. For dry matter production, nutrient requirements for Korean pine and broad-leaved forests are 8.92 kg Nt^{-1} and 15.50 kg Nt^{-1}, respectively (Cheng et al., 1987). If soil fertility is the first priority, broad-leaved forests are not suggested for commercial plantation because of the higher nutrient loss from the ecosystem when forest products are removed.

Fertilization

There is an increasing demand for forest products. Fertilizers can be used to improve forest production and shorten the rotation time. N is commonly limited for forest productivity, and application of N fertilizer is generally effective. Whenever the soil nutrient capital is small, implying a small annual net increment, the general conclusion is that the N loss in product

Table 7. Nutrient return in pure Chinese fir plantation and the mixture with *M. macclurei* through various processes

Stand type	Litter fall (kg ha^{-1} a^{-1})	N ratio of return to uptake	Fine root turnover (times a^{-1})	Total amount of nitogen return through fine-root decomposition (kg ha^{-1} a^{-1})
Pure plantation	473	0.10	1.29	0.32
Mixed plantation	1087	0.17	1.40	2.59

Table 8. Effect of fertilizers on height growth of three-year old Masson pine plantations (Xiao, 1998)

Fertilizer	Dosage (g per tree)	Effective element percentage (%)	Tree height (cm)	Increase percentage (%)
Urea	125	N 46%	148.3	2.6
Lime superphosphate	125	P_2O_5 15%	172.5**	19.2
Potassium chlorite	125	K_2O 50%	161.3*	11.6
Compound fertilizer	125	N, P, K: 15% respectively	183.8**	27.2
None	0	none	144.5	0

$^{*}p < 0.05$; $^{**}p < 0.01$.

removal could reduce the growth of subsequent productions, but this loss could be compensated for by fertilizer addition. Most fertilization trials were made on different plantation stands at young ages, such as Chinese fir, Masson pine (*Pinus massoniana* Lamb.), poplar, etc. These plantations are fast-growing and cultured for commercial objective in short rotations. Timber removement could be the main cause of nutrient depletion for these forest sites, so fertilizer addition is the main approach to compensate the nutrient loss (Li et al., 1996a). N fertilizer application has little or no effect on growth of Masson pine trees on acidic red soil in which phosphorus is generally the limiting element for tree growth in southern China. Application of lime superphosphate significantly increased the height growth by 19.4% ($p < 0.01$), and the compound fertilizer of N, P and K by 27.2% ($p < 0.01$) (Table 8). A common conclusion of different fertilizer trials is that the compound fertilizer of N, P and K in appropriate proportions can show best promoting effect on tree growth (Li et al., 1996a; Xiao, 1998). Fertilizer application can improve soil fertility in terms of organic matter and available nutrients simultaneously (Li et al., 1996b).

Another fertilizer test on a 12-year-old elliottii pine (*Pinus elliottii* Engelm.) plantation shows better effect on growth. At the end of 4 years' fertilizer application experiment, the mean diameter at breast height (DBH) increased by 41.9% to 48.9%, and standing stock by 36.7% to 63.0%, and the ratio of input to output was high ranging from 4.3 to 7.1 (Li et al., 1993). N fertilizer showed no effect neither and the complex of N, K, P fertilizer in proportion had the best effect. It can be assumed that nitrogen is not the limiting element in forest soils of southern China.

A test on conifers shows that the response from a single fertilizer application is short, reaching a maximum at 2 to 6 years after application and disappearing after 5 to 10 years. The efficiencies of forest to use fertilizers are comparatively low (10–50%) for a single fertilization (Xu, 1987). Thus, small frequent fertilizer applications are recommended instead of a single large application.

References

Aber JD, Melillo JM, McClaugherty CA & Eshleman KN (1983) Potential sinks for mineralized nitrogen following disturbance in forest ecosystems. In: Hallberg R (ed) Environmental biogeochemistry. Ecol Bull (Stockholm) 35: 179–192

Bormann FH & Likens GE (1981) Pattern and process in a forested ecosystem. Springer-Verlag, New York

Briones MJI & Ineson P (1996) Decomposition of eucalyptus leaves in litter mixtures. Soil Biol Biochem 28: 1381–1388

Chen CY, Zhang JW, Deng SJ, Wang SL & Liao LP (1989) Effect of acid rain on forest ecosystems in Southwestern China. In: Article collections on acid rain study, pp 466–475, edited by China Environmental Science Society, China environmental science press

Cheng BR, Xu GS, Gen XY & Zhang GL (1987) The nutrient cycling in the Korean pine-broad-leaved forest of the Changbai mountains. Acta Pedologica Sinica 24(2): 160–169

Cheng BR, Xu GS, Gen XY & Zhang GL (1993) Nutrient input of throughfall in a pine-spruce-fir forest of Changbai mountain. Chin J Appl Ecol 4(4): 447–449

Cooke GW (1967) The control of soil fertility. Crosby Lockwood and Son Ltd

Feng ZW, Chen CY, Zhang JW, Zeng SY & Zhao JL (1988) A coniferous broad-leaved mixed plantation forest with higher productivity and ecological harmony in subtropical China – a case study on mixed plantation of *Cunninghamia lanceolata* and *Michelia macclurei* var. *sublanea*. Acta Phytoecologica et Geobotanica Sinica 21(3): 165–180

Li WG, Liu FD, Zhang CF & Zhang YX (1996a) A test of fertilizer dosage and proportion on Masson pine stand. Guizhou Forestry Science and Technology, 24(1): 29–32

Li WG, Liu FD, Zhang CF & Zhang YX (1996b) Effect of fertilization on soil fertility under young Masson pine plantations. Guizhou Forestry Science and Technology 24(4): 27–30

Li YQ, Chen DD, Xu QY, Dai ZD & Ye WD (1993) Effect of fertilizer use on a middle-aged eliottii pine plantation. 268-276 In: Forest and Soil, edited by The Profession Committee of Forest Soil. Beijing: China Science and Technology Press

Liao LP & Chen CY (1991) Effects of simulated acid rain on root growth of *Cunninghamia lanceolata* and *Schima superba* saplings planted in acidified soil. J Environ Sci (China) 3(2): 45–52

Liao LP, Chen CY, Zhang JW & Deng SJ (1995) Turnoverof fine roots in pure and mixed *Cunninghamia lanceolata* and *Michelia macclurei* var. *sublanea* forest, Chin J Appl Ecol 6(1): 7–10

Liao LP, Ineson P and Yang YH (1997) Decomposition of foliar litter in mixture I. A microcosm study. Chin J Appl Ecol 8(5): 459–464

Liao LP, Yang YJ, Deng SJ & Gao H (1998) Distribution, decomposition and nutrient return of fine-roots in pure Chinese fir and *M. macclurei* plantations and the mixture. Acta Ecologica Sinica. (In press)

Liu ZZ, Zhang LH, Ma CX & Xu Y (1995) Studies on turnover of nitrogen in the soils under two kinds of forests, Acta Ecologica Sinica 15(B): 61–67

Morrison IK (1984) Acid rain – A review of literature on acid deposition effects in forest ecosystems. Forestry abstracts 45(8): 483–506

Run HH (1994) Studies on nutrient cycling in three forest types in the hilly regions of southern Jiangshu Province. In: Long-term research on China's forest ecosystems, pp 104–111, edited by Department of Science and Technology, Ministry of Forestry, Northeast forestry University Press

Xiao SP (1998) A preliminary study on young Masson pine plantation. Guangxi Forestry Science 27(2): 95–97

Xu GS (1987) Nitrogen distribution and cycle in temperate forest ecosystem. Translated report on terrestrial ecology 1: 1–13

Xu GS, Zhang YH & Liu CP (1995a) Nutrient cycling in a Korean pine broad-leaved forest in the temperate zone. Acta Ecologica Sinica 15(B): 47–53

Xu GS, Zhang YH & Liu CP (1995b) Biological nutrient cycling in a Korean pine-spruce-fir forest stand in Changbai mountain. Acta Ecologica Sinica 15(B): 54–60

Zhang GH & Zhao DW (1989) Acid rain. Beijing: China Environmental Science Press (in Chinese)

Zhang JW, Chen CY, Deng SJ, Liao LP & Wang SL (1993) Effect of acid rain on forest growth, In: Study on the techniques of pollution prevention, pp 805–813, edited by China National Environmental Protection Bureau, Science Press, Beijing

Zhang YH, Xu GX & Liu CP (1995) Hydrochemical characteristics in spruce-fir forest ecosystems of Changbai mountain. Acta Ecologica Sinica 15(B): 41–46