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Estimation and Mapping of Nitrogen Uptake by Forest in South Korea

Cheol-Hee Kim · Il-Soo Park · Sang-Kyun Kim · Hye-Young Son · Jong-Jae Lee · Jae-Bum Lee · Chang-Keun Song · Jae-Myun Shim

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Abstract Regional air pollution in northeast Asia is an emerging environmental problem requiring long-term impact assessment of acidic deposition. In this study, the gridded distribution of nitrogen uptake led by both growing forests and harvested biomass for eight tree species: *Japanese Larch*, *Red pine*, *Korean pine*, *Oak tree*, *Chestnut*, *Other Conifers*, *Other broad leaved trees*, and *Mixed forest* was identified to estimate critical loads for nitrogen over South Korea. The gridded spatial distribution of averaged nitrogen uptake was mapped by 0.125° Latitude × 0.125° Longitude resolution. The results showed that net uptake of nitrogen led by both growth and harvested biomass was totaled at 438 mol_c ha^{-1} $year^{-1}$ among which harvested biomass contribution was estimated to be 25 mol_c ha^{-1} $year^{-1}$, yielding a very small fraction of total nitrogen uptake presumably due to the younger stages of forest in South Korea.

C.-H. Kim (✉) · H.-Y. Son · J.-J. Lee
Division of Earth Environmental System,
Pusan National University,
Busan 609-735, South Korea
e-mail: chkim2@pusan.ac.kr

I.-S. Park · S.-K. Kim · J.-B. Lee · C.-K. Song
National Institute of Environmental Research,
Incheon 404-170, South Korea

J.-M. Shim
Korea Meteorological Administration,
Seoul 156-720, South Korea

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1 Introduction

Northeast Asia has experienced rapid economic growth and industrialization. Long-term impacts of sulfur and nitrogen deposition by both long-range transport and local emissions have been recognized as those of growing concern during the last and most recent decades. The increase of acidifying by air pollutant emissions is expected to continue for the next several years, due mainly to the accelerated use of fossil fuel burning systems planned in many Asian nations. This situation has led to the necessity of collaborative environmental research and development of measures in the transboundary air pollution field in Northeast Asia. In this light the Tripartite Environment Ministers Meeting that included Korea, China and Japan, was held in order to strengthen mutual understanding and cooperation among the Northeastern countries. Implemented were joint feasibility activities by the Long-range Transboundary Project (LTP), begun among three countries in 1995 for collaborative research on monitoring and modeling the transboundary air pollutants. In that original LTP meeting, the methodology of calculating source–receptor relationships over Northeast Asia became a starting point, and mapping of critical loads based on steady-state Simple Mass Balance (SMB) Model was adopted for the long-term impacts assessment of long range transport of air pollutants over the Northeast area.

Critical loads are defined as threshold values of an exposure to pollutants below which significant harmful effects on specified sensitivity elements of the environment do not occur (Nilsson and Grennfelt 1988). Specifically, for the receptor of soils, critical loads are the highest depositional load of no harmful effects on forest and soil ecosystem, which is therefore related to the indirect soil-meditated effects of atmospheric acidic deposition on forest condition (De Vries 1992, De Vries et al. 1993; Nilsson and Grennfelt 1988). So far the concept of critical loads of acid forming pollutants for soil is used as a quantitative tool for assessing forest ecosystem sensitivity to acid deposition (Park and Bashkin 2001). Since mapping of critical loads is providing the data which forms the basis for international negotiations on abatement strategies for emissions of transboundary air pollutants (Hettelingh et al. 1992; Hodson and Langan 1999; Hornung et al. 1995; Kuylenstierna et al. 1998; Logan and Hornung 1992; Park and Bashkin 2001; Posch et al. 2003, 2005; Warfvinge and Sverdrup 1995), it has been widely accepted throughout Europe.

Critical loads over Northeast Asia have been determined for acidic forming pollutants but are generally conceptualized by two pollutants: sulfur and nitrogen. Park and Lee (2001) have estimated the maximum critical load for sulfur and its exceedance level defined as the difference between the actual sulfur deposition and the critical load in South Korea. They found that more than 40% of the ecosystems in South Korea exceeded the present sulfur deposition, and expected that the situation would become worse for the case of considering combined loadings of sulfur and nitrogen.

However, aside from the critical load for sulfur, estimating maximum nitrogen critical load requires both databases of critical load for sulfur and further processes such as nitrogen uptake from the net growth uptake of nitrogen by the forest, and the denitrification process in soil layer. Besides, calculation of eutrophication (the nutrient effect) of nitrogen, which an important criteria for setting critical loads of nitrogen, is also needed, and required to be compared with maximum critical load for nitrogen in order to set the acceptable limit of the deposition of nitrogen over the target area.

Here, mapping of net nitrogen uptake rate requires the spatial coverage of various forest types, and database including both forest growth rate and harvested biomass in gridded domain is needed for the precise calculation of nitrogen uptake. Although considerable effort in South Korea has gone into available input data, the estimation of the nitrogen uptake has been impeded by the lack of ambient data and uncertainties such as its availability of forest/species spatial distribution, non-representative forest properties, and other unclassified species of forests over target domain.

This paper presents the mapped estimates of uptake of nitrogen by forest ecosystem calculated from various national literatures with the grid scale of 11 km (0.125° Latitude)×14 km (0.125° Longitude). The province-based national statistics in South Korea were used and the Geographical Information System (GIS) technique was employed to avoid the underlying errors arising from both the distribution of forest/species and spatial resolution. Empirical values from national literatures are used for the calculation of nitrogen uptake over the Korean forest ecosystem. Spatial distribution patterns of nitrogen uptake are also discussed in detail. Figure 1 shows the locations of 15 provinces in South Korea.

2 Estimation of Nitrogen Uptake

2.1 Maximum Critical Loads of Nitrogen and Nitrogen Uptake

In the steady-state Simple Mass Balance (SMB) model for a homogeneous soil compartment considering the main source and sinks of sulfur and nitrogen (Posch et al. 2003), the charge balance of the ions in the soil leachate flux leads to the critical load for sulfur (S) and nitrogen (N) for constant sinks (De Vries 1992):

$$\mathrm{CL_{max}(S)} = \mathrm{BC_{dep}} - Cl_{\mathrm{dep}} + \mathrm{BC_w} - \mathrm{BC_u} - \mathrm{Alk_{le(crit)}} \tag{1}$$

$$\mathrm{CL_{max}(N)} = N_1 + N_u + \frac{\mathrm{CL_{max}(S)}}{1 - f_{de}} \tag{2}$$

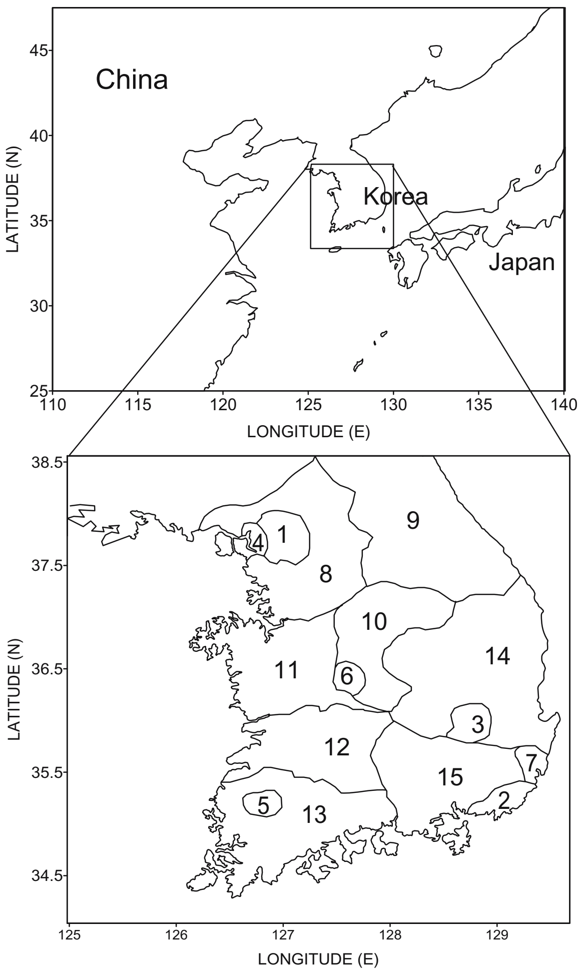


Fig. 1 Locations of 15 provinces in South Korea. Denotation of each number means 1:Seoul, 2:Pusan, 3:Daegu, 4:Incheon, 5:Gwangju, 6:Daejon, 7:Ulsan, 8:Kyonggi, 9:Kangwon, 10: Chungbuk, 11:Chungnam, 12:Chunbuk, 13:Chunnam, 14: Kyungbuk, 15:Kyungnam, respectively

and $CL_{max}(S)$: maximum critical load for S, BC_{dep}: base cation total deposition Cl_{dep}: Cl total deposition, BC_w: weathering of base cation, BC_u: net uptake of base cation by forest, $AlK_{le(crit)}$: critical alkalinity leaching rate, $CL_{max}(N)$: maximum critical load for N, N_i: net soil N immobilization, N_u: N uptake by vegetation, and f_{de}: denitrification fraction. All equations are expressed in eq ha^{-1} $year^{-1}$. In Eq. (2), immobilization (N_i) and net uptake of nitrogen (N_u) by forests are needed for the estimation of maximum nitrogen critical load.

The effect of N deposition on nutrient status (Posch et al. 2003) can be assess by the critical load for nutrient nitrogen, $CL_{nut}(N)$, which is given by

$$CL_{nut}(N) = N_1 + N_u + \frac{N_{le(crit)}}{1 - f_{de}} \tag{3}$$

When considering the critical load of acidifying and nutrient nitrogen simultaneously, two possibilities arise. One is $CL_{nut}(N) \geq CL_{max}(N)$ and the other is $CL_{nut}(N) \leq CL_{max}(N)$. The first case $CL_{nut}(N)$ can be ignored so that the maximum permissible N deposition by $CL_{max}(N)$, while the second case $CL_{nut}(N)$ limits the maximum permissible N deposition.

2.2 Method, Data and Underlying Assumptions

We considered eight predominant tree species in South Korean forests: four Coniferous (*Japanese Larch*, *Red pine*, *Korean pine,* and *Other Coniferous trees*), three Deciduous (*Oaks*, *Chestnut*, and *Other Deciduous trees*), and *Mixed forest* were taken into account. However, in this study, spatial distribution of forest coverage in each grid of 11 km (0.125° Latitude)×14 km (0.125° Longitude) over the whole domain is a key parameter in estimating spatial distribution of nitrogen uptake. Here we used a recent satellite image of Korean forest and the Geographic Information System (GIS) technique to identify the gridded coverage of various forests in South Korea. ArcInfo GIS architecture provides the spatial analysis technique so-called vector analysis technique. As illustrated in Fig. 2, the forest map (Korea Forest Institute 2006) was analyzed by converting the ArcInfo Interchangable format and decomposing the image data. As a result, the image of forest map was found to be consisting of 746 classes overlaid in total. We produced eight tree species classes in each grid cell, and estimated forest coverage areas and coverage percentage (%) in each grid. The geographic mapping method was described in Arp et al. (2001).

Uptake of nitrogen can be estimated primarily from the net growth biomass of plant communities and harvested biomass. We did not include the effect of forest fires that could not have a considerable impact on uptake of N over South Korea. Generally, uptake by growth biomass should be assumed that, over the long term, net uptake is equal to the removal in harvested biomass. In this study, we considered both growth rate of biomass and harvested biomass for the

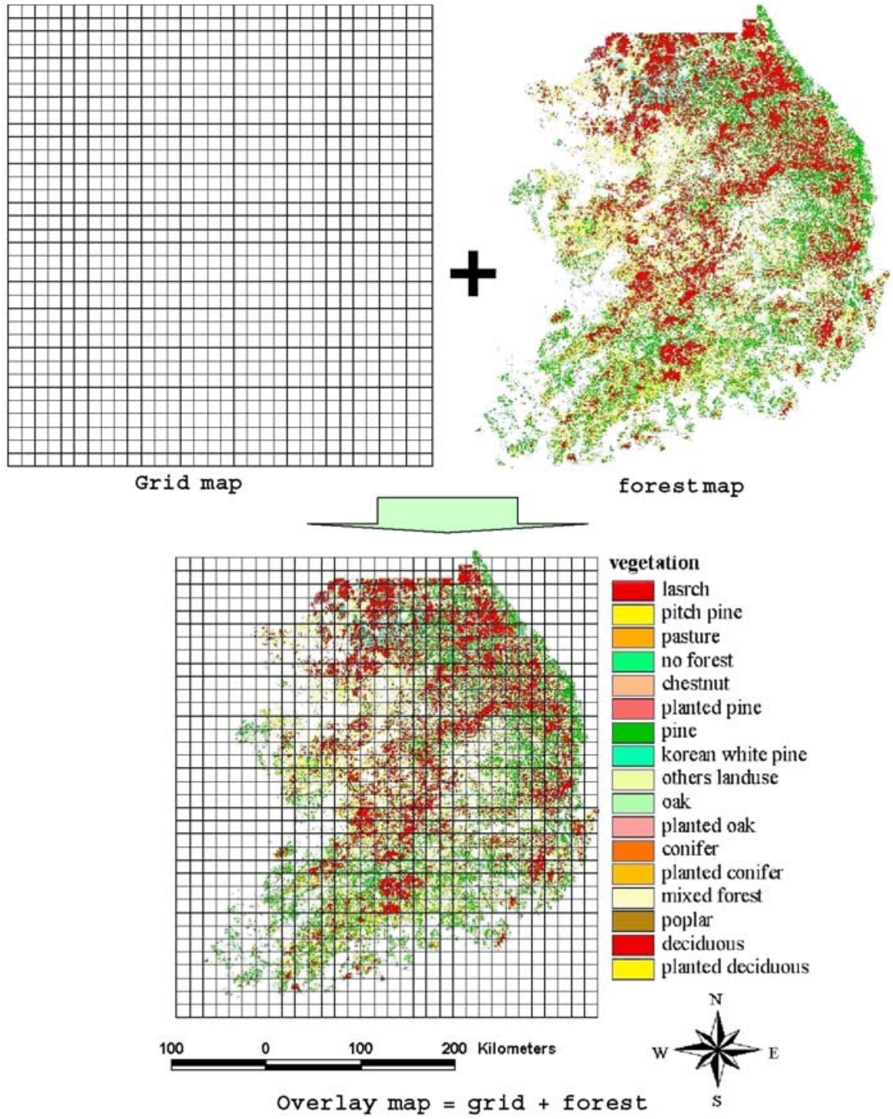


Fig. 2 Schematic diagram for the estimation of the forest coverage using the Geographical Information System

estimation of nitrogen uptake, although, in Korea, the harvested biomass is reported to be a small fraction (≈5%) of the net growth biomass due mainly to the fact that most of the trees in South Korean forest are younger than the rotation period (Korea Forest Service 2000). In order to estimate the uptake of nitrogen by growth biomass, data of net primary production (NPP) was used.

As a first step to estimate NPP, the data of both reported average stem growth rate which is estimated from the diameter of breast height obtained by the field observations, and ratio from the branch to stem ratio was collected. The average stem growth rate was reported in National statistical yearbook of forestry (Korea Forest Service 2005) covering 10 years from 1995 to 2004 of South Korea. Next, NPP, the average growth rate of both stem and branch, was estimated from the average stem growth rate. The NPP is expressed as:

$$\mathrm{NPP} = k_{gr} \cdot \rho_{st}\left(1 + f_{br/st}\right) \quad (4)$$

where k_{gr} is the annual average growth rate (m^3 ha^{-1} year^{-1}), ρ_{st} the density of stemwood (kg m^{-3}), and $f_{\mathrm{br/st}}$ the branch to stem ratio, respectively. Similarly, the annual net growth uptake (N_{u}) can be calculated as (De Vries et al. 1993):

$$N_u = k_{gr} \cdot \rho_{st}\left(N_{st} + f_{br/st} \cdot N_{br}\right), \quad (5)$$

Table 1 The density of stemwood, the branch to stem ratio ($f_{br/st}$), and mean concentrations of nitrogen (N) in stems and branches

Forest type (tree species)	Stem density (kg/m^3)	$f_{br/st}$	Mean concentration (eq/kg)	
			N_{st}	N_{br}
Coniferous				
Japanese Larch	401	0.15	0.10	0.39
Red Pine	401	0.26	0.09	0.25
Korean Pine	377	0.26	0.09	0.25
Other coniferous trees	356	0.26	0.14	0.29
Deciduous				
Oaks	700	0.30	0.15	0.44
Chestnut	695	0.25	0.11	0.31
Other Deciduous trees	633	0.33	0.14	0.39
Mixed forest				
Mixed forest	526	0.30	0.16	0.31

where N_{st} and N_{br} are the content of N in stems and branches (eq kg^{-1}), respectively. In Eq. (4), the annual average growth rate (k_{gr}) can be derived from the data of the density of stemwood (ρ_{st}), the branch to stem ratio ($f_{br/st}$), and NPP of eight tree species. Average ρ_{st} and $f_{br/st}$ were estimated based on Korea Forest Service (2005). The content of nitrogen in stems (N_{st}) and branches (N_{br}) was obtained from both the Korea Forest Service (2005) and foreign reports (Cho and Kim 1989; De Vries 1992; Kwak and Kim 1992; Mun et al. 1977; UBA (Umbelt Bundes Amt) 1996). All of the values are listed in Table 1. We calculated the annual average growth rate (k_{gr}) estimated from the NPP in each of the 15 administrative South Korean regions as indicated in Fig. 1, and yielded the distributions of N uptake (N_u) based on the values listed on Table 1.

All growth biomass of each province during the period from 1995 to 2004 was taken into account, but annual timber production reported by the Korea Forest Service was used during the period from 2002 to 2004 for the calculation of harvested biomass. This is due to the restriction that only total timber production statistics rather than province-based timber production had been available before 2002 in Korea. As the branch production was not included in the statistics, the empirical constants such as content of nitrogen in stems (N_{st}) and branches (N_{br}), density of stemwood (ρ_{st}), and the ratio of branch to stem ratio ($f_{br/st}$) are equally used for both growing and harvested biomass. Finally the estimated uptake of nitrogen by the processes of both growth and harvested biomass from different forest types in each province is apportioned to each 11 km×14 km

Table 2 Forest area, estimated annual mean net production, and uptake of nitrogen (N) by growing above ground biomass in forests over South Korea from 1995 to 2004

Forest type (tree species)	Forest area (10^{3}ha)	Net primary production (NPP) (kg DM ha^{-1} year^{-1})	Uptake of N (mol$_c$ ha^{-1} year^{-1})
Coniferous	2,748 (43.9%)	1,558	266
Japanese Larch	469 (17%)	1,652	227
Red Pine	1,519 (55.3%)	1,671	205
Korean Pine	233 (8.5%)	1,628	200
Other Coniferous trees	527 (19.2%)	1,118	191
Deciduous	1,673 (26.8%)	3,809	769
Oaks	1457 (87.1%)	–[a]	–[a]
Chestnut	75 (4.5%)	1,398	210
Other Deciduous trees	141 (8.4%)	3,923[b]	792[b]
Mixed Forest	1,834 (29.3%)	2,476	482
Mixed forest	1,834 (100%)	2,476	482
Mean		2,237	438
Total	6,255		

[a] The data was not reported but classified to Other Deciduous trees in the literature.

[b] The data of Other Deciduous trees described here includes [a] Oak trees.

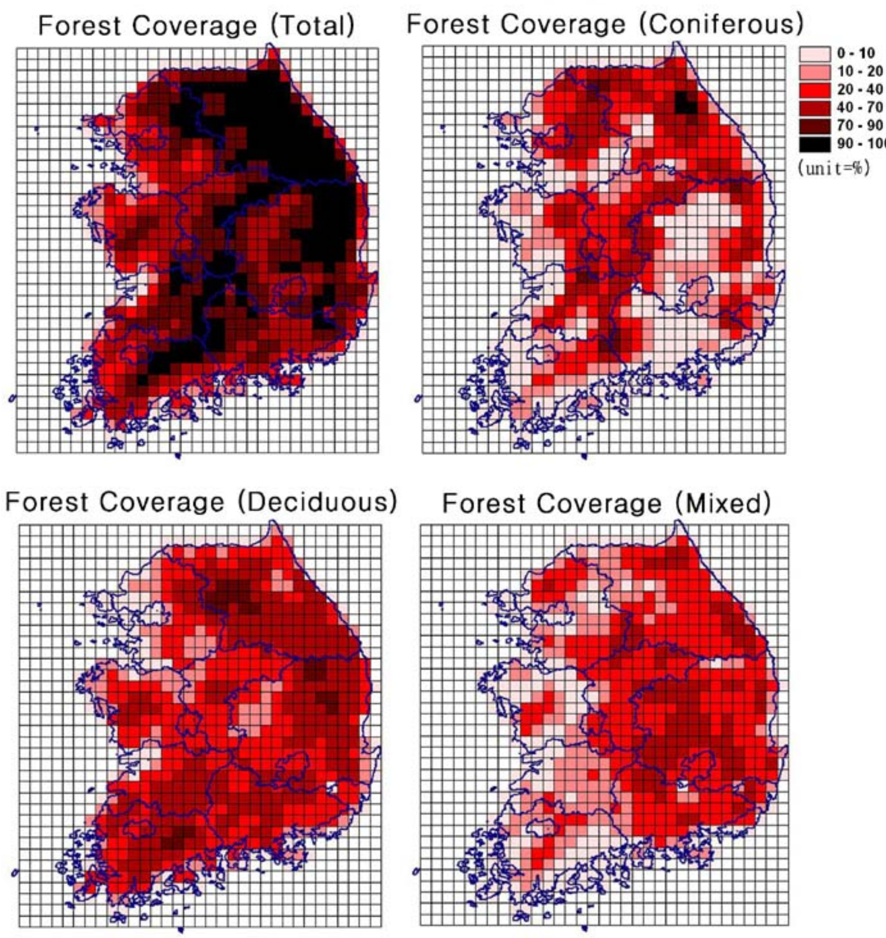
gridded domain according to the eight forest coverage.

3 Results

Table 2 summarizes the forest coverage (%), the annual net primary production (NPP) and total uptake of nitrogen by both growth and harvested biomass for each of the eight tree species in South Korean forests. The forests of coniferous, deciduous and mixed forests occupy about 43.9%, 26.8% and 29.3% over the whole area of South Korea, respectively. Of the Coniferous area, *Red Pine* (55.3%) mostly occupies, and *Oaks* (87.1%) predominated among Deciduous. According to Table 2, South Korean total NPP of Deciduous area shows higher value of NPP than Coniferous area approximately by a factor of 2, while the coverage (%) of Coniferous area is much more than that of Deciduous as in Fig. 4, resulting from the differences of productivity and the ratio of branch to stem ratio ($f_{br/st}$) between Coniferous and Deciduous as listed in Table 1. In Table 2, it is also noted that uptake of nitrogen was 266, 769 and 482 mol$_c$ ha^{-1} year^{-1} on average by Coniferous and Deciduous, respectively. This is comparable to the values of nitrogen uptake reported by De Vries (1993) in Dutch where those are 300 and 500 mol$_c$ ha^{-1} year^{-1} by Coniferous and Deciduous, respectively, showing very similar values in comparison with that estimated in this study.

Figure 3 shows the spatial distributions of the forest coverage (%) in 11 km×14 km gridded domain. Areas of high Coniferous and Deciduous

Fig. 3 Averaged annual variations of growing stocks (m^3 ha^{-1}) in each administrative province from 1995 to 2004



percent concentrations are found mostly in the northwestern and southeastern parts of the Korean peninsula, whereas areas of mixed forest are overall found in the southeastern parts of Korea (Fig. 3b–d), resulting in the high value of total forest coverage over the East and Southwest area of South Korea where relatively higher mountainous areas are distributed.

Figure 4 shows changes of growing forest (m^3 year^{-1} ha^{-1}) and net primary production (NPP) (kg DM ha^{-1} year^{-1}) for each province in South Korea. Due to the fact that each NPP of eight tree species is intimately involved in the density of stemwood (ρ_{st}) and the branch to stem ratio ($f_{br/st}$) as indicated in Eq. (4), lower values of Coniferous are found in most provinces, although change of forest storage is relatively higher than those of Deciduous and Mixed forests. Overall net primary production (NPP) of Deciduous and Mixed forests is in the range of from 2 to 4 ton DM ha^{-1} year^{-1}, but Coniferous shows relatively lower NPP. Figure 5 shows the spatial distribution of net primary production (NPP) by the growing forests over South Korea. The grids of NPP ranging from 0.5 to 2 ton DM ha^{-1} year^{-1} are occupying 54.7% of the South Korean forests. Spatially the northwestern part of Korean peninsula shows relatively higher NPP with the average of more than 2.5 ton DM ha^{-1} year^{-1} due to the larger

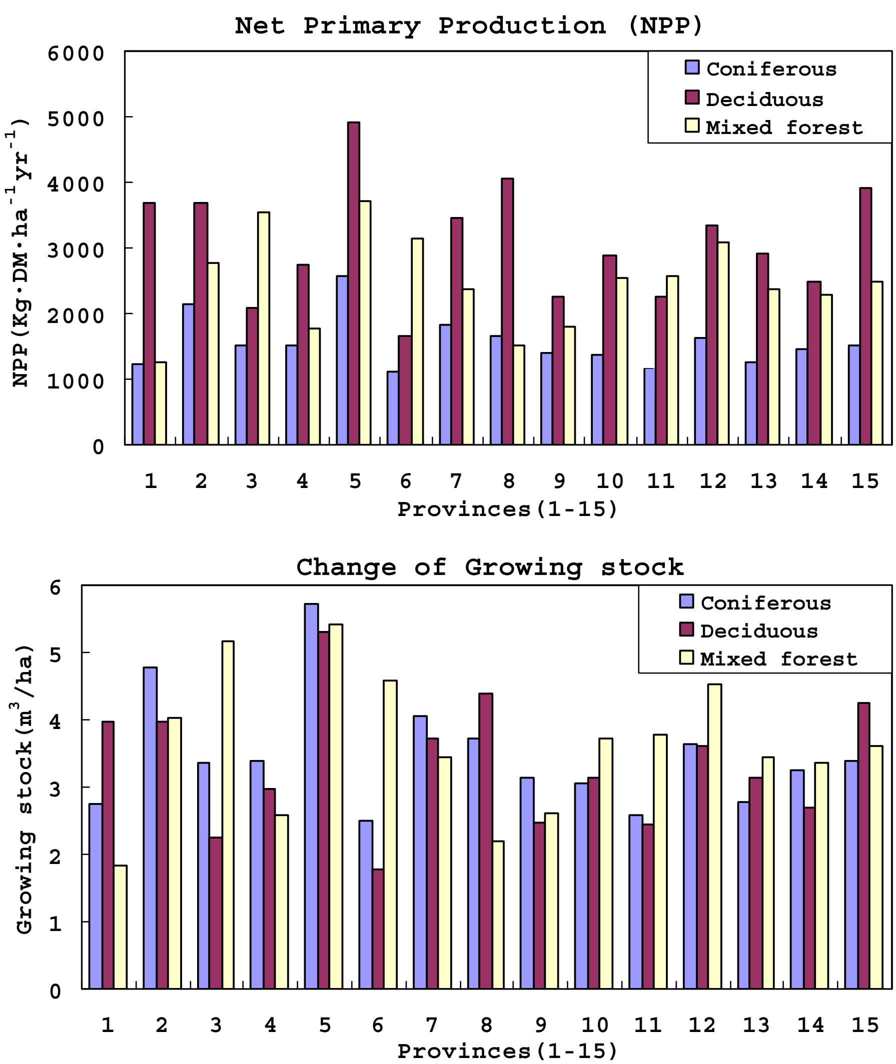


Fig. 4 Spatial distributions of forest coverage (%) in the grid scale of 11 km×14 km over South Korea

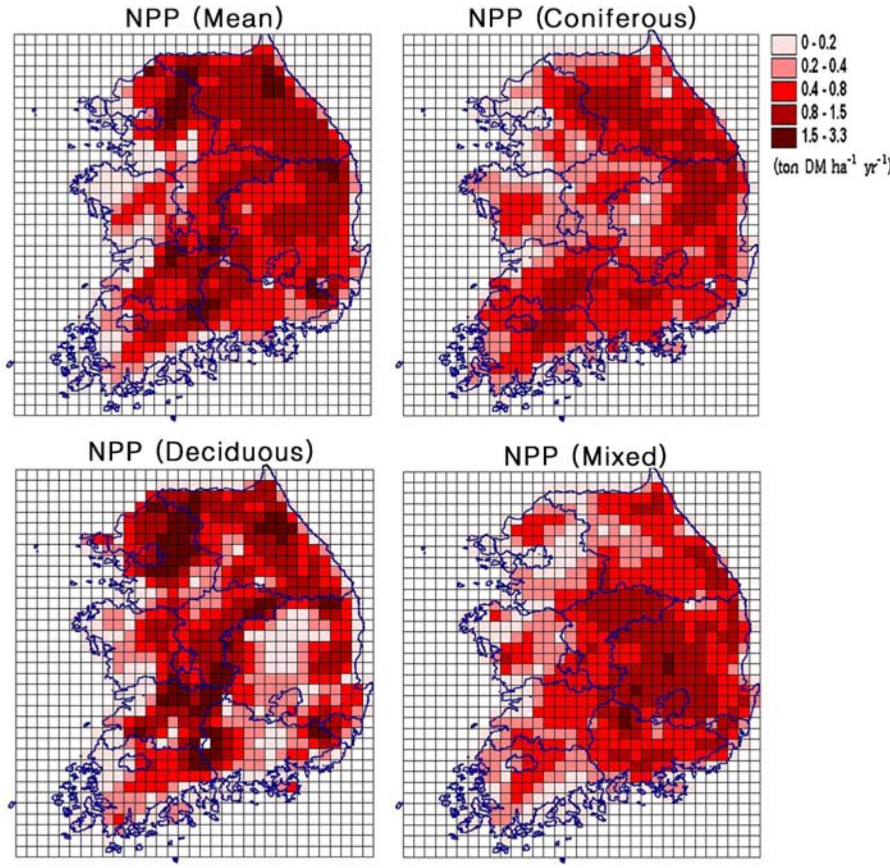


Fig. 5 Spatial distributions of annual mean net primary production (NPP; ton DM ha^{-1} year^{-1}) by different forests including stem and branch

changes of growing Deciduous forest in both Province 8 (Kyonggi) and Province 1 (Seoul) denoted in Fig. 1.

Given the timber production in each province, uptake of nitrogen by harvesting forests was calculated. According to national statistics, the annual rates of timber production over 15 provinces show a slowly decreasing trend during the period from 1999 to 2004. Recent timber production data for each tree species was used in this study to estimate harvested biomass in South Korea. Table 3 listed timber production in 2004 for each province. It shows that *Oak* occupies 26.5% among Deciduous and *Red Pine* 19.8% among total timber production. Here various constants listed in Table 1 such as nitrogen in stems and branches, density of stemwood, and the ratio of branch to stem ratio were equally used to calculate annual mean uptake by harvested forest. Although spatial distribution patterns of timber production over South Korea were not shown, harvested biomass with the value of less than 200 kg DM ha^{-1} year^{-1} is estimated at 90% of total South Korean forests. As a result, the estimated uptake of nitrogen through the timber production process was estimated to be only 25 mol$_c$ ha^{-1} year^{-1} on average, indicating a very small fraction (≈5%) of total uptake of nitrogen over South Korea in comparison with the estimation from growth biomass as listed in Table 2. This is suggesting that South Korean forests are at a very much younger stage than those of other European countries reported in the Rains-Asia Program (World Bank 1994). This result implies that South Korean forest is expected to be on increasing trend of nitrogen uptake, suggesting non steady state situation and thereby its underlying uncertainties when formulating the critical load for nitrogen by using the steady state mass balance method.

Figure 6 shows the spatial distribution of mean nitrogen uptake estimated from both the growing and harvested biomass of Korean forests. The annual mean nitrogen uptake is about 438 eq ha^{-1} year^{-1}, with the maximum uptake of 685 eq ha^{-1} year^{-1} around the southwestern area of South Korea. Of the

Table 3 Timber production (m^3) in 2004 based on the data from Korea Forest Service (2005)

Provinces	Total	Timber production (m^3)						
		Coniferous				Deciduous		
		Japanese Larch	*Red Pine*	*Korean Pine*	*Other Coniferous trees*	*Chestnut*	*Oaks*	*Other Deciduous trees*
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	1,479	0	0	98	138	282	961	0
5	894	0	264	0	520	0	110	0
6	12,753	490	555	0	6,328	0	5,366	14
7	0	0	0	0	0	0	0	0
8	158,192	14,762	4,205	20,649	55,950	1,922	50,323	10,381
9	236,378	47,415	100,416	28,128	6,429	257	53,181	552
10	123,657	21,729	10,985	496	28,405	0	60,927	1,115
11	248,623	10,757	61,286	61	101,837	1,410	56,780	16,492
12	235,323	11,059	49,397	556	146,050	1,596	23,832	2,833
13	132,741	0	13,894	0	81,032	4,646	32,143	1,026
14	148,850	8,550	12,475	1,502	4,529	55,175	65,060	1,559
15	28,486	1,225	8,912	11,500	3,449	328	2,823	249
Total	1,327,376	115,987	262,389	62,990	434,667	65,616	351,506	34,221

Locations of each province were denoted in Fig. 1.

entire uptake of nitrogen, 95% is contributed by the forest growth of biomass. The range of from 200 to 400 mol_c ha^{-1} $year^{-1}$ is predominantly covering 67.1% of the total area of forest. Spatially the northwestern area and the southern part of the Korean peninsula show higher uptake of nitrogen due to the relatively larger NPP (larger uptake of nitrogen) of Deciduous in both Province 8 and Province 1 denoted in Fig. 1. However the previous studies suggested relatively lower stemwood nitrogen concentration for the matured stage of most European forests. Therefore, expecting the current Korean forest forwarding matured forest, further studies such as collecting more recent data including the nitrogen concentration in stem and branch, and branch to stem ratio are going to be conducted in order to update the present result of this study.

4 Conclusions

In this study, uptake of nitrogen was calculated and mapped for the estimation of critical load of nitrogen in South Korea. The Geographic Information System is applied for the calculation of uptake of nitrogen by eight tree species: four Coniferous (*Japanese Larch*, *Red pine*, *Korean pine,* and *Other Coniferous trees*), three Deciduous (*Oaks*, *Chestnut*, and *Other Deciduous trees*), and *Mixed forest*. Nitrogen uptake process was estimated from the effects of both growing and harvested biomass of eight forest types using the statistical yearbook of forestry during the period from 1995 to 2004, but the effect of forest fires was not included in this calculation due to the lack of available data. The annual average growth biomass was calculated from the data of growing stocks, and harvested biomass was estimated from timber production in each administrative province over South Korea. Other data obtained from Korean National literature was used. The calculated growth and harvest uptake in each province is apportioned according to the forest area of the grid, mapping distribution of uptake of nitrogen with the resolution of 11 km (0.125° Latitude)×14 km (0.125° Longitude) over South Korea.

The results showed that total net production of the stocked forests from the whole stocked area of South Korea (6.26×10^6 ha) was about 1.6×10^7 ton DM/

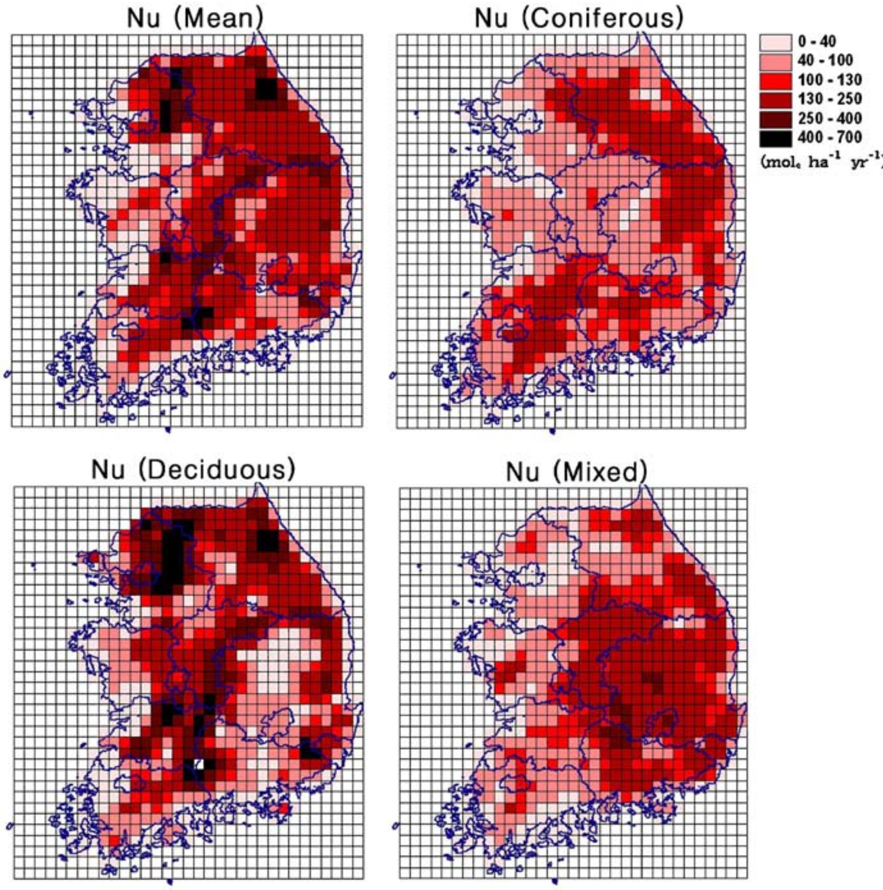


Fig. 6 Spatial distributions of the annual mean total nitrogen uptake (mol$_c$ ha^{-1} year^{-1}) by different forests including stem and branch

year, and the total harvested biomass calculated from timber production data was approximately 1.3×10^6 ton DM/year. The estimated net growth uptake of nitrogen was 438 mol$_c$ ha^{-1} year^{-1} on average, and the content of nitrogen in the harvested biomass was 25 molc ha^{-1} year^{-1}, yielding a very small harvesting fraction of total nitrogen uptake. Total net uptake of nitrogen from growth and harvest by stocked forests in South Korea was totaled at 2.579×10^9 mol$_c$/year.

The estimated uptake of nitrogen per unit area was 266, 769 and 482 mol$_c$ ha^{-1} year^{-1} by Coniferous, Deciduous and Mixed forest, respectively. Spatially the northwest and the south of the Korean peninsula were estimated to be relatively higher in uptake of nitrogen with the maximum value of more than 600 mol$_c$ ha^{-1} year^{-1} due to the larger uptake of nitrogen by Deciduous. These values are found to be similar in comparison with the reported values in Dutch by De Vries (1993).

In this study we have made every effort to estimate more accurately each parameter that is related to the evaluation of nitrogen uptake process for the calculation of maximum critical load of nitrogen. Also immobilization of nitrogen and soil type dependency of the denitrification fraction are going to be estimated for mapping of critical load for nitrogen over South Korea. As well, identifying the critical load for nitrogen and its exceedance level will be continued for the impact assessment of transboundary air pollutants over the Northeast Asia as a component of the Long-range Transport Project (LTP) meeting.

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