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NEECF: a project of nutrient enrichment experiments in China's forests

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Abstract

Anthropogenic nitrogen (N) emissions to atmosphere have increased dramatically in China since 1980s, and this increase has aroused great concerns on its ecological impacts on terrestrial ecosystems. Previous studies have showed that terrestrial ecosystems in China are acting as a large carbon (C) sink, but its potential in the future remains largely uncertain. So far little work on the impacts of the N deposition on C sequestration in China's terrestrial ecosystems has been assessed at a national scale. Aiming to assess and predict how ecological processes especially the C cycling respond to the increasing N deposition in China's forests, recently researchers from Peking University and their partners have established a manipulation experimental network on the ecological effects of the N deposition: Nutrient Enrichment Experiments in China's Forests Project (NEECF). The NEECF comprises 10 experiments at 7 sites located from north to south China, covering major zonal forest vegetation in eastern China from boreal forest in Greater Khingan Mountains to tropical forests in Hainan Island. This paper introduces the framework of the NEECF project and its potential policy implications.

Keywords: carbon sequestration, nitrogen deposition, forest ecosystem, nutrient enrichment experiments in China's forests, China

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INTRODUCTION

Anthropogenic nitrogen (N) emissions from agricultural (e.g. animal husbandry and N fertilizer application) and industrial activities (e.g. fuel burning and N fertilizer production) have been increasing dramatically since the industrial revolution (Galloway *et al.* 2004). Consequently elevated N deposition has aroused great concerns on its ecological impacts on terrestrial and aquatic ecosystems. In Europe, cross-site N manipulation experiments, such as the NITREX (Wright and Rasmussen 1998; Wright and van Breeman 1995) and EXMAN (Wright and Rasmussen, 1998), have been established to assess the impacts of N deposition on forest ecosystems since the late 1980s. In North America, there have also been several chronic nitrogen addition experiments since the late 1980s (Aber *et al.* 1993; Magill *et al.* 1996, 2004). The impacts of N deposition on terrestrial ecosystems vary with the status of soil N availability and forest types. In N limited ecosystems, N deposition enhances plant growth and increases net primary productivity (e.g. Magnani *et al.* 2007; Thomas *et al.* 2010). However, when exceeding the critical loads, N deposition exerts negative impacts on the health and function of ecosystems, such as biodiversity loss (Bobbink *et al.* 2010; Clark and Tilman 2008; Sala *et al.* 2000; Stevens *et al.* 2004), soil acidification (de Vries *et al.* 2007; Richter and Markewitz 2001), eutrophication and nutrient imbalances (Aber *et al.* 1989, 1998) and increased vulnerability to environmental stress (Aerts and Bobbink 1999; Witzell and Shevtsova 2004).

The large uncertainty of the fertilization effect of N deposition on carbon (C) sequestration in forest ecosystems has aroused an intense debate. In temperate and boreal forests in Europe and North America, regardless of the effects of forest management and natural disturbances (e.g. fire disturbance), Magnani *et al.* (2007) found that C sequestration was not significantly correlated to temperature and precipitation, and N deposition was the main driving force on C sequestration with the effect value of as high as C:N = 725:1. Sutton *et al.* (2008) analyzed the effects of total N deposition on net ecosystem productivity in 22 European forests and found the effect value to be C:N = 149:1. However, the effect value was reduced to C:N = 50~75:1 after excluding the contribution of climatic factors. Högberg (2007) estimated that input of 1 kg N to the temperate forest ecosystem would increase biomass carbon sequestration by 30 kg C and soil organic matter by 10 kg C, causing a total effect value of 40:1 (C:N). Considering all the main factors affecting forest growth, de Vries *et al.* (2008) found that N deposition had an effect value of C: N = 20~40:1 on forest biomass C sequestration in European forests. Further, given an effect value of N deposition on soil C sequestration of C:N = 10~30:1, the total effect on whole ecosystem C sequestration would be C:N = 30~70:1. In the forest ecosystems in north-western and central USA, the average effect value of N deposition on C sequestration of aboveground tree biomass was C:N = 61:1 (51~82:1) and that of the total C sequestration (above and below ground biomass) was C:N = 73:1 (61~98:1; Thomas *et al.* 2010). The fate of the N in forest ecosystems greatly influences total effect of N deposition because of much higher effect value in biomass than that in soil. For instance, analyzing the data of multisite ^{15}N labeling experiments in temperate forests, Nadelhoffer *et al.* (1999) found that soil rather than tree biomass was primary sink of N input that indicated a minor contribution of N deposition to C sequestration. Modeling estimation also showed large variation in the contribution of N deposition to the global forest C sequestration, ranging from 0.1 Pg C year^{-1} to more than 2 Pg C year^{-1} (Holland *et al.* 1997; Schindler and Bayley 1993; Townsend *et al* 1996). In the changing global environment with increasing atmospheric CO_2 concentrations and warming climate, it is very important to assess the effects of N deposition on the ecosystem C cycling in order to reduce the uncertainty in ecosystem C sequestration (Heimann and Reichstein 2008; Hungate *et al.* 2003; Reay *et al.* 2008; Reich *et al.* 2006).

Carbon cycling of forest ecosystem in East Asia plays a significant role in the regional climate systems and biogeochemical cycles (Fang *et al.* 2010). East Asia has become one hotspot with high N deposition (Dentener *et al.* 2006). The enhanced N deposition due to rapid agricultural and industrial development and urban expansion has aroused great concerns of its ecological impacts on terrestrial and aquatic ecosystems especially in the eastern and central China (Liu *et al.* 2011). In China, understanding of the environmental effects from N deposition initially arose from the concern of acid deposition in the 1980s (Zhao and Sun 1986). The growing N deposition has aroused great concerns since the successful controlling of the increase of sulfur deposition from 2000s (Zhao *et al.* 2009). To assess the impacts of N deposition on China's forest ecosystems, there have been several N deposition simulation experiments since the 2000s, and most of them were short-term studies (e.g. Fan *et al.* 2007; Mo *et al.* 2008) or conducted on tree seedlings (e.g. Liu *et al.* 2012; Yao *et al.* 2011). Due to lack of long-term and cross-site experimental studies, modeling validation and impact assessment of N deposition at a national scale are extremely hindered. During the period 1981–2000, the average C sink capacity of Chinese terrestrial ecosystems was estimated as 0.19–0.26 Pg C year^{-1}, absorbing ≈28–37% of C emissions from fossil fuel combustion within the same period (Piao *et al.* 2009). However, knowledge gaps still exist for the driving strength of N deposition on this C sink. In the background of climate change, it is urgently needed to integratively assess the effects of N deposition on ecosystem health and functions in China's forests. Aiming to assess and predict how ecological processes especially the C cycling respond to the increasing N deposition in China's forests, since 2010 researchers from Peking University and their colleagues have established a manipulation experimental network: Nutrient Enrichment Experiments in China's Forests Project (NEECF). The NEECF project comprises 10 experiments at 7 sites located from the north to the south, covering major typical forests in eastern China from boreal forest in Greater Khingan Mountains to tropical forest in Hainan Island. This paper introduces the framework of the NEECF project and its potential policy implications.

FRAMEWORK OF NEECF PROJECT

Site information

The NEECF project currently has 7 sites that cover the typical forests in eastern China from boreal forest in Greater Khingan Mountains to tropical forest in Hainan Island. These 7 sites locate from north to south include Genhe (GH), Wuying (WY), Saihanba (SHB), Donglingshan (DLS), Guniujiang (GNJ), Wuyishan (WYS) and Jianfengling (JFL) (Fig. 1a).

Table 1 shows general information on the NEECF sites. *Genhe site* (GH, Inner Mongolia Autonomous Region), representing an area of about 1.8×10^5 km^2 of boreal forest in north-east China, is located in the north-western slope of the Greater Khingan Mountains, which is the southern edge of Eurasia boreal forest. Larch (*Larix gmelinii*) is the dominant tree species of the forest type, and its distribution ranges are susceptible to climate change (Leng *et al.* 2008). *Wuying site* (WY, Heilongjiang Province) is located in the middle of the southern slope of Lesser Khingan Mountains with the mixed forest of broad-leaved trees and Korean pine (*Pinus koraiensis*). *Saihanba site* (SHB, Hebei Province) is at a junction of the Mongolian Plateau, Greater Khingan Mountains and Yinshan Mountains. The site is characterized by its large coverage of Chinese larch (*Larix principis-rupprechtii*) and pine (*Pinus sylvestnis* var. *mongolica*) plantations. *Donglingshan site* (DLS, Beijing) is located at eastern part of Taihang Mountains with the typical zonal vegetation of temperate deciduous broad-leaved forest, such as East-Liaoning oak (*Quercus liaotungensis*) forest. *Guniujiang site* (GNJ, Anhui Province) at the northern limit of subtropical evergreen broadleaf forest, is dominated by evergreen fagus species, such as *Castanopsis eyrei*, *Cyclobalanopsis myrsinaefolia*, *Cyclobalanopsis glauca and Lithocarpus brevicaudatus*. *Wuyishan site* (WYS, Fujian Province) is covered by mid-subtropical evergreen broadleaf forest,

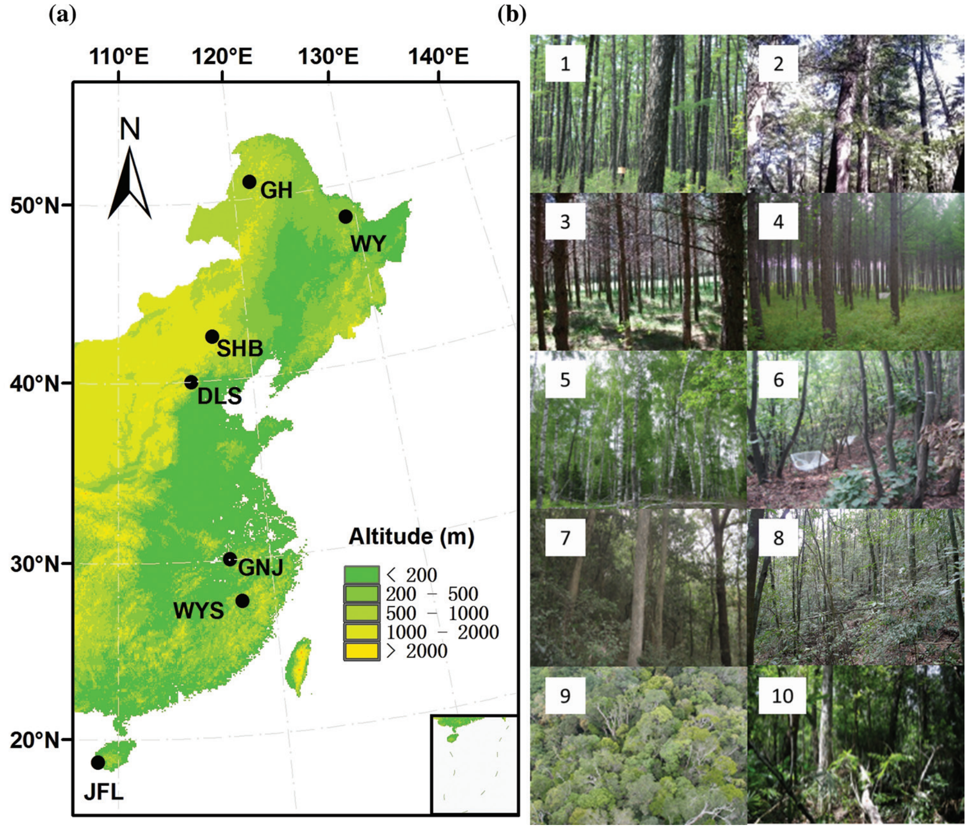

Figure 1: locations of NEECF sites (a) and photographs of forest structure in each site (b). Seven sites (a) are located from north to south, including Genhe (GH), Wuying (WY), Saihanba (SHB), Donglingshan (DLS), Guniujiang (GNJ), Wuyishan (WYS), and Jianfengling (JFL). Photographs (b) show the view of the ten experimental forests, including: 1 primary larch forest at Genhe, 2 broadleaved Korean pine mixed forest at Wuying, 3 pine plantation at Saihanba, 4 larch plantation at Saihanba, 5 birch forest at Donglingshan, 6 East-Liaoning oak forest at Donglingshan, 7 Sweet Oachestnut forest at Guniujiang, 8 *Castanopsis carlesii* forest at Wuyishan, 9 primary tropical montane rain forest at Jianfengling and 10 secondary tropical montane rain forest at Jianfengling.

Table 1: general information on NEECF sites

Site	Location	Altitude (m)	AMT (°C)	AMP (mm)	Growing season	Soil type	Vegetation type
GH	50°56′N, 121°30′E	825	−5.4	481	June–August	Brown coniferous forest soil	Boreal forest
WY	48°07′N, 129°11′E	350	−0.5	654	May–September	Dark brown soil	Temperate broadleaved & conifer mixed forest
SHB	42°25′N, 117°15′E	1400	−1.4	450	May–September	Sandy soil	Plantation
DLS	39°58′N, 115°26′E	1300	5.4	505	May–September	Montane brown soil	Temperate deciduous broadleaved forest
GNJ	30°1′N, 117°21′E	375	9.2	1650	Whole year	Brown earth	Subtropical evergreen broadleaved forest
WYS	27°39′N, 117°57′E	700	18.0	1889	Whole year	Yellow-red soil	Subtropical evergreen broadleaved forest
JFL	18°43′N,108°53′E	870	24.7	2265	Whole year	Yellow soil	Tropical montane rain forest

Notes: The table shows site location (latitude, longitude and altitude), climate (annual mean temperature (AMT), annual mean precipitation (AMP) and duration of growing season), soil and vegetation type for the seven NEECF sites: Genhe (GH), Wuying (WY), Saihanba (SHB), Donglingshan (DLS), Guniujiang (GNJ), Wuyishan (WYS), and Jianfengling (JFL).

with dominant species of *Castanopsis carlesii*, *Schima superba*, *Castanopsis tibetana*, *Castanopsis eyrei*, *Cyclobalanopsis glauca* and *castanopsis fargesii*. *Jianfengling site* (JFL, Hainan Province) is located at the mountain area with the largest well-protected tropical montane rain forest in China. In sum, the NEECF covers major zonal forests in eastern China with apparent climatic gradients (Fig. 2) and provides an excellent field for experimental research.

Forest information

Ten representative forests have been chosen for the NEECF Project (Fig.1b). The primary larch forest represents the southern boreal forest in Greater Khingan Mountains (Du *et al*. 2013). The broad-leaved Korean pine mixed forest dominates forest cover in Lesser Khingan Mountains. Chinese larch (*Larix principis-rupprechtii*) and pine (*Pinus sylvestnis* var. *mongolica*) are most common species of the plantations in north China. The East-Liaoning oak (*Quercus liaotungensis*) forest and birch forest are chosen to represent the temperate deciduous broad-leaved forest in eastern China. The sweet oachestnut forest and *Castanopsis carlesii* forest are important types of the evergreen broad-leafed forest in eastern China. Primary and secondary tropical montane rain forests in Mountain Jianfengling, Hainan are chosen for the experiments in the tropical region (Zhou *et al*. 2013). The general information on NEECF forests is shown in Table 2 including forest age, diameter at breast height, mean tree height, soil C, N and P content, soil pH, soil N mineralization and ambient N deposition. The N deposition ranges from 5.5 to 15.0 kg N ha^{-1} $year^{-1}$ in boreal and temperate forests, and from 10.6 to 25.0 kg N ha^{-1} $year^{-1}$in subtropical and tropical forests. The relatively low rates of the background N deposition in these forests are an advantage for the nutrient enrichment experiments to track the entire change of the ecosystem processes in response to the simulated N deposition.

Research scheme

Long-term nutrient addition experiments have been started at sites of NEECF since 2010. The research scheme of the NEECF project is shown as Fig. 3. According to the aims of the NEECF project, a series of basic monitoring parameters (see Table 3) and standard methods of data collection have been implemented. The monitoring variables in the nutrient (mainly N) enrichment experiments include the following five categories: (i) global change factors (e.g. ambient N deposition, temperature and precipitation), (ii) soil properties and nutrient cycling (e.g. soil C, N and P content and N mineralization), (iii) biological process factors (e.g. physiological response of plant and microbial organisms), (iv) community species composition and (v) C cycling fluxes (e.g. NPP (net primary productivity) and soil CO_2 effluxes). In addition, more parameters are encouraged to be measured based on the specific scientific questions for each site. Data quality is carefully controlled and input to the meta-database to support further data analysis. Statistical methods and approaches are applied to assess the impacts of increasing N deposition on major ecological processes, especially the C cycling. Further, we are to develop theoretical and empirical models to predict responses of C sequestration to N deposition in future scenarios at ecosystem and/or national scales. We expect that the project will substantially contribute to the scientific basis for the C management of national forest ecosystems and regulation policy to control the N emissions.

Experimental design

Knowledge of how N deposition affects the ecosystem processes is mostly achieved from the N deposition simulation experiments. Could these experiments accurately simulate the ecological effects of N deposition? Defects of experiment design are likely to lead to misleading conclusions. Carefully designed N deposition simulation experiment

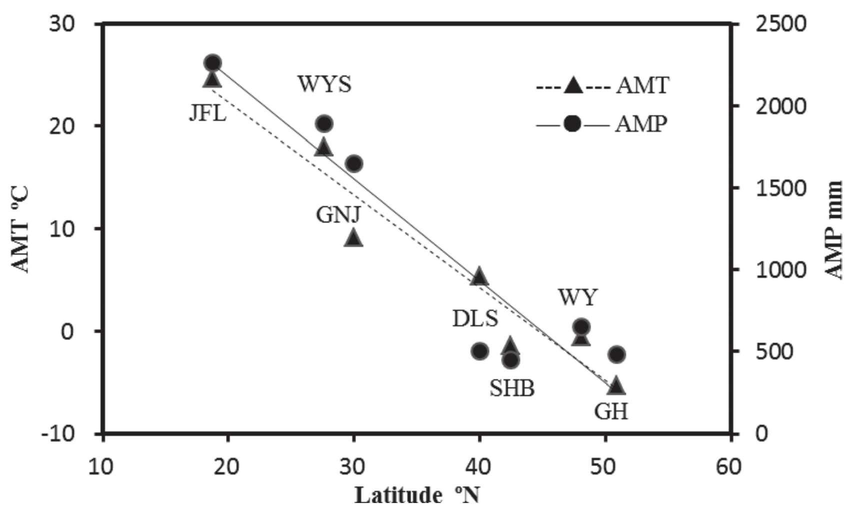

Figure 2: annual mean temperature (AMT, °C) and annual mean precipitation (AMP, mm) at NEECF sites. The x-axis, left y-axis and right y-axis indicate latitude, AMT and AMP, respectively.

Table 2: experimental forests used in the NEECF project

Station	Forest type	Forest age (yr)	DBH (cm)	Height (m)	Soil C (g/kg)	Soil N (g/kg)	Soil P (g/kg)	Soil pH	N mineralization (kg N ha^{-1} yr^{-1})	N deposition (kg N ha^{-1} yr^{-1})
GH	Primary larch forest	>300	16.9	15.5	29.73	4.10	1.20	4.70	—	5.5
WY	Broadleaved Korean pine mixed forest	191	23.7	—	—	—	—	—	—	7.0
SHB	Pine plantation	30	12.1	10.1	13.40	1.17	—	6.47	24.80	6.0
	Larch plantation	45	19.8	15.8	29.54	2.23	—	6.29	—	6.0
DLS	East-Liaoning oak forest	70~80	10.9	7.0	—	—	—	—	—	15.0
	Birch forest	70~80	13.6	10.2	—	—	—	—	—	15.0
GNJ	Sweet oachestnut forest	300	13.7	—	10.23	0.81	0.25	4.60	97.14	10.6
WYS	*Castanopsis carlesii* forest	45	11.8	15.0	4.10	0.29	—	—	—	16.0
JFL	Primary tropical montane rain forest	300	5.8	5.4	35.50	1.40	0.12	4.60	105.6	25.0
	Secondary tropical montane rain forest	50	5.2	5.4	35.50	1.40	0.12	4.60	117.4	25.0

Note: The table includes the forest information (forest type, forest age, DBH, Height), soil information (soil C, N and P content, soil pH and soil N mineralization) and ambient N deposition for the forests of NEECF sites. The dashes indicate data not available.

should thoroughly consider the following aspects: (i) N species (e.g. NH_4NO_3, $NaNO_3$, NH_4Cl and urea), (ii) the time and frequency of the N application, (ii) the dose of N used for each application, (iv) the way of the application (e.g. spray as solutions or power, application from the canopy or on the forest floor) and (v) the ambient N input from atmosphere and N availability from forest soils. By reviewing a large number of previous N addition experiments (see Table 4), we have carefully designed the nutrient enrichment experiment for the NEECF project. Helpful suggestions from many colleagues have largely contributed to the improvement of the experiment design (see Acknowledgment).

The NEECF experiment generally develops a 4 (or 3) treatments ×3 replicates random block design (see Table 5). It is essential to choose the N species and doses of each application. Inorganic N (NH_4^+ and NO_3^-) generally accounts for more than 75% of the total N deposition, and therefore application of ammonium nitrate (NH_4NO_3) is reasonable to simulate the N deposition. The NEECF experiment includes the following treatments: control (no N added), low N (20 kg N ha^{-1} $year^{-1}$), moderate N (50 kg N ha^{-1} $year^{-1}$), and high N (100 kg N ha^{-1} $year^{-1}$). The low N treatment was set according to the suggested critical loads of 20 kg N ha^{-1} $year^{-1}$ for most vulnerable forests (Bobbink *et al*. 2010). The moderate and high N treatments were set at the rate of 50 and 100 kg N ha^{-1} $year^{-1}$, which were used for most of other N enrichment experiments in China. Totally twelve (or nine) 20×20 m^2 plots with similar stand density have been set up. In each plot, only the central 15×15 m^2 area, which was further divided into nine 5×5 m^2 subplots, was used for measurement and sampling. Between adjacent plots, a buffering area with distance >10 m was set up. The N additions are applied to the forest floor with 30 L concentrated solution of ammonium nitrate (NH_4NO_3) using a backpack sprayer. The control plots

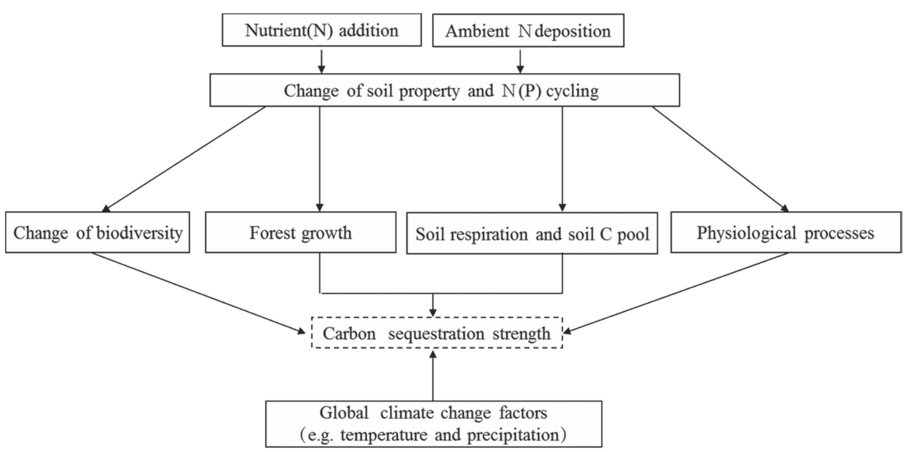

Figure 3: research scheme of the NEECF project.

Table 3: mandatory monitoring items of the NEECF project

No.	Item	Content
1	N deposition	Bulk N deposition
2	Soil N	NH_4^+, NO_3^- and total soil N content
3	Soil P	Soil available P and total P content
4	Soil C	SOC and total C content
5	N mineralization	Rate of N mineralization
6	Soil pH	Soil pH
7	Meteorological factors	Soil and air temperature, and moisture
8	Tree growth	Annual increment of DBH and tree height
9	Grass biomass	Species, coverage, height and biomass
10	Shrub biomass	Species, coverage, BD, height and biomass
11	Root biomass	Root biomass and growth
12	Litter production	Monthly litter production
13	Soil respiration	Rt, Rh and Ra
14	Litter decomposition	Rate of litter decomposition
15	Stoichiometry	Foliar and root C, N and P content

Abbreviations: DBH = diameter at breast height, BD = basal diameter, Rt = total soil respiration, Rh= heterotrophic respiration, Ra= autotrophic respiration.

receive 30 L water with no N added. The N addition is carried out monthly during the growing season, and no treatments are done during winter with snow cover. Unfortunately, we have to use urea instead of ammonium nitrate at sites (SHB and DLS) near Beijing region because of the local safety regulations.

POLICY IMPLICATIONS

Compared with that in 1980, NH_3 emissions in China have doubled and NO_x emissions have increased by a factor of 4 by 2005 (Liu *et al.* 2011). According to the Twelfth 5-Year Plan, China will reduce NO_x emissions by 10% in 2015 against the 2010 levels, but there are still no control regulations of NH_3 emissions in China. With the growth of the GDP (Gross Domestic Product) and growing requirement of living quality, demands on food production and energy consumption in China will continue to increase. The total N emissions (NO_x and NH_3) and consequent N deposition will remain at high levels in the next few decades. China has formulated series of policies and corresponding actions to combating climate change and the adverse effects thereof. Recently, China has set an ambitious target to reduce the CO_2 emissions per unit of GDP by 40–45% in 2020 compared with the levels in 2005. Afforestation and forest management with scientific planning are implemented as essential measures to strengthen the C sink in Chinese forests. Targets have been set to expand forest coverage by 40 million hectares and to increase forest stock volume by 1.3 billion m^3 in 2020 compared with the 2005 levels. The NEECF project has established a national network of nutrient enrichment experiments in major forests in eastern China to monitor the C cycling and its response to the simulated N deposition. Modeling approaches will be used to assess the driving strength of the increasing N deposition on national forest C sequestration. Therefore, the NEECF project will be expected to greatly contribute to the scientific base of C sink management of national forest ecosystems and regulation policy to control the N pollution in the future.

Table 4: summary of referential N enrichment experiments

Site	Treatments (Kg N $ha^{-1}yr^{-1}$)	Plot area (m^2)	Repeats	N species	N Application methods	References
Harvard forest, USA	0, 50, 100	30 × 30	3	NH_4NO_3	Spray N solutions monthly	Aber *et al.* 1993
Norrliden, Sweden	0, 34, 68, 108	30 × 30	3	NH_4NO_3	Spray N solutions annually	Strengbom *et al.* 2001 (8.58)
South Finland	0, 25	30 × 30	4	$(NH_4)_2SO_4$	Spray N solutions annually	Mäpikää 1995 (8.10)
Michigan, USA	0, 80	15 × 30	3	$NaNO_3$	Apply N powders monthly	Waldrop *et al.* 2004 (8.67)
	0, 30	50 × 50	3	$NaNO_3$	Apply N powders monthly	Eddy *et al.* 2008 (7.86)
	0, 30	30 × 30	3	$NaNO_3$	Apply N powders monthly	Smemo *et al.* 2006 (8.56)
Aber Forest, UK	0, 35, 75	15 × 15	3	NH_4NO_3/ $NaNO_3$	Spray N solutions weekly	Emmett *et al.* 1995 (7.86)
Western Jutland, Denmark	0, 35	15 × 15	3	NH_4NO_3	Apply N powders monthly	Gundersen 1998 (7.93)
Bear Brooks, USA	0, 18–28, 56–61	15 × 15	3	HNO_3	Spray N solutions	Magill *et al.* 1996
Dinghushan, China	0, 50, 100, 150	10 × 20	3	NH_4NO_3	Spray N solutions monthly	Mo *et al.* 2006 (8.10)
Chiyoda, Japan	0, 168, 336	1.89	2	HNO_3 / NH_4NO_3	Spray N solutions monthly	Nagakura *et al.* 2006 (8.15)
Whim Moss, UK	0, 16, 32, 64	12.6	4	NH_4Cl/ $NaNO_3$	Spray N solutions after rain	Skinner *et al.* 2006 (8.30)

Note: The table lists site, treatments, plot area, repeats of experiments, N species and N application methods for several N enrichment experiments reviewed in the NEECF Project.

Table 5: design of nutrient (N and P) enrichment experiments of each NEECF site

Station	Forest type	Treatments (kg $m^{-2}yr^{-1}$)	N species	Start time
GH	Primary *Larix gmelinii* forest	N: 0, 20, 50, 100	NH_4NO_3	2010.5
WY	Broadleaved Korean pine mixed forest	N: 0, 20, 50, 100	NH_4NO_3	2010.5
SHB	*Pinus sylvestnis* var. *mongolica* plantation	N: 0, 50, 100, 150	Urea	2009.8
	Larix principis-rupprechtii plantation	N: 0, 20, 50	Urea	2010.5
DLS	*Quercus liaotungensis* forest	N: 0, 50, 100	Urea	2011.7
	Betula platyphylla forest	N: 0, 50, 100	Urea	2011.7
GNJ	*Castanopsis eyrei* forest	N: 0, 50, 100	NH_4NO_3	2011.3
WYS	*Castanopsis carlesii* forest	N: 0, 50, 100	NH_4NO_3	2011.6
JFL	Primary tropical montane rain forest	N: 0, 25, 50, 100	NH_4NO_3	2010.9
	Secondary tropical montane rain forest	N+P:50+50 P:50	$Ca(H_2PO4)_2$	

Notes: The table summarizes the treatments, N species and start time of the nutrient enrichment experiments for each forest type at the seven sites of NEECF.

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Conflict of interest statement. None declared.

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