Global-scale modelling of potential changes in terrestrial nitrogen cycle from a growing nitrogen deposition

Z.G. Li, L. Lin, M. Sagisaka, P. Yang, W.B. Wu

*Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China
b Research Institute of Science for Safety and Sustainability (RISS), National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8569, Japan

Abstract

Given the fact of growing deposition of atmospheric nitrogen (N) in terrestrial biosphere, it is critical to get a better understanding of potential changes in terrestrial N cycle causing from the increasing deposited N. In this study, a global scale process-based Terrestrial Biogeochemical Nitrogen Cycle (TBNC) model originally developed by Lin et al., (2000) has been improved and applied to quantify the changes of terrestrial N cycle under the scenarios of N deposition at conditions in 1993 and 2050 (Galloway et al., 2004). Sensitivity analysis and empirical validation indicated the reliability of the model for addressing the complexity of current N cycle changes and its capacity for investigating long-term scenarios in the future. Under the growing rates of 34% and 77% as in NO\textsubscript{x} (all oxidized forms of N including N\textsubscript{2}O) and NH\textsubscript{x} (NH\textsubscript{3} and NH\textsubscript{4}\textsuperscript{+}), depositions, the model results show that ammonium and nitrate in surface soil are predicted to increase about 10% and 23%, while other N pools have no obvious change. Major N fluxes in soil, i.e. denitrification, ammonium volatilization, nitrate leaching, gaseous losses (mainly N\textsubscript{2}O and NO) and nitrification, are predicted to increase about 10-25%. The responses of major biome classes show that an increase rate of 10% as in ammonium accumulation is predicted to occur in temperate forests, while temperate shrublands and grasslands are the most important nitrate reservoir with an increase rate of 20% in response to future N depositions. Generally, TBNC model could help us to quantitatively understand and explain the causes and consequences of spatiotemporal changes of global N cycle, and thereby provide a means of estimating the potential responses of terrestrial ecosystems to alteration of the global N cycle, especially from human impacts.

© 2011 Published by Elsevier B.V. Selection and/or peer-review under responsibility of School of Environment, Beijing Normal University. Open access under CC BY-NC-ND license.

Keywords: Terrestrial Biogeochemical Nitrogen Cycle (TBNC) model, steady state model, global nitrogen cycle, nitrogen deposition, anthropogenic disturbance

1. Introduction

Until recently, projections of climate change are usually made based on the classical coupled climate carbon (C) cycle models without consideration of N excess or limitation in the terrestrial biosphere, however, understanding the mechanisms of the increased availability of N interacts with other biogeochemical element cycles is thought to be crucial for accurate projections of future climate change[1]. As a response, a variety of biogeochemical cycle models based on the interactions among the C, N and water cycles have been developed in recent decades, including DyN (Dynamic Nitrogen) [2], DNDC (Denitrification-Decomposition) [3], TEM (Terrestrial Ecosystem Model) [4, 5], and Hybrid v3.0 [6], and many others. All these models are driven by the climate variables of surface and soil, and employ...
algorithms to simulate important N transformation processes such as the exchange of N between the surface and the atmosphere through denitrification and deposition, the assimilation and release of N through plant uptake, fixation and turnover, and the decomposition of organic matter and the transformation of N in soil. As such, they provide an important means to simulate regional and global C and N cycles, and to assess the impacts of climate variability and its long-term change on these cycles [7]. While most of the work has so far been limited to the simulation of a hypothetical natural N cycle in the terrestrial biosphere, the processes and amounts of realistic N cycling, that is greatly modified by the human activities, are seldom included in a global-scale N cycle modelling framework.

Nowadays humans have dramatically altered the global N cycle. Three anthropogenic processes, including fossil fuel combustion, artificial N fertilizer production, and legume and rice cultivation, are responsible for converting unreactive N to various forms of reactive N [8, 9]. In the 1990s, these three sources of anthropogenic N to the environment amounted to more than 160 teragrams (Tg) N per year [10-12], which is much more than supply from natural biological N fixation on land (110 Tg N per year) [1]. As a result, a large anthropogenic increase in global N deposition during the 20th century has been proposed as a contributory effect [13, 14]. There are also critical questions about the fate and impact of the N deposited to terrestrial, freshwater, and marine realms [15]. Recently, a global gridded estimates of atmospheric N deposition for the years 1860 and 1993 and projections for the year 2050 are provided by Galloway et al., (2004) [16-18].

In this study, the estimates of N deposition in 1993 and 2050 were derived and taken as the scenarios of current and future N deposition, noted as DEPO-I, and DEPO-II respectively. On this basis, Terrestrial Biogeochemical Nitrogen Cycle (TBNC) model, developed by Lin et al., (2000) [19], is improved and used as a means to estimate and demonstrate the potential changes and responses of N cycle to future N deposition. Finally, the limitations of this model and the direction of future improvements are also discussed.

2. Methodology

2.1. Improvement of TBNC model

The TBNC model was initially designed for a global view of the biogeochemical N cycle based on the mass balance concept of C and N in the terrestrial ecosystems [19]. To improve simulation accuracy and efficiency, all of the model parameters and the relative formula on the N processes have been updated and integrated into TBNC model partly from the existing N cycle models [2-5].

2.1.1. Overview of the improved TBNC model

Following the current understanding on global C and N cycle, major pathways for C and N cycling are illustrated as shown in Fig.1, which also show some points of control between the two cycles. The central point for the TBN model is the allocation logic between the C and N cycles. C and N allocation is controlled by fixed C: N ratios, so new growth is dependent on there being an adequate supply of both C, from the gross photosynthesis process, and N, taken up by the plants from the soil. In the case of excess C coming from the photosynthesis predictions, with respect to the N available from the soil, gross photosynthesis is reduced, effectively attenuating the N use efficiency under N-limiting conditions. N is introduced into the biosphere in various organic and inorganic N compounds from litter of plant tissues, fixation by symbiotic or non-symbiotic bacteria, and deposition. Simultaneously, N is removed from the soil by plant uptake, leaching, volatilization, denitrification and other gaseous emissions. These movements and transformations of the various N compounds throughout the cycle can be represented by the 10 major ecological processes occurring among the three compartments. Processes in the vegetation compartment comprises (1) plant photosynthesis, (2) plant autotrophic respiration, and (3) plant N uptake; the organic-soil compartment includes (4) organic C&N decomposition in litter, active and stable SON pools, (5) biological N2-fixation; the inorganic-soil compartment includes (6) nitrification, (7) NH3 volatilization, (8) nitrate leaching, (9) nitrate and ammonium deposition, (10) denitrification. Among these processes, process (3) uses an annual time step, and the others use a daily time step.
2.1.2. Model equilibrium analysis

Generally, equilibrium of an ecosystem model refers to a steady status in which model state variables reach a dynamical balance (e.g., dead tissues are replaced by new tissues of the same quantities). As the first step, the steady state for each vegetation type in each cell is monitored independently, and the model was to start all soils with no organic matter, and plants with a very low initial biomass, and let the soil organic matter and plant biomass upgrade over many cycles until equilibrium conditions are reached, which is defined by a variation in total soil N averaged over several hundred years of less than 0.005% per year. We present results for fluxes (such as NPP and annual N uptake) as values for the last simulation year and for all state variables as values at the end of the last simulation day.

\[
\frac{d(Veg_N)}{dt} = N_{\text{uptake}} - N_{\text{fall}} 
\]  

(1)
\[
\frac{d(Lit\_N)}{dt} = N\_fall\_amm + N\_fix - N\_Lit\_dec - N\_Lit\_hum\_active - N\_Lit\_hum\_stable
\]

\[
\frac{d(SON\_Active)}{dt} = N\_Lit\_hum\_active + Amm\_imob - N\_Active\_min
\]

\[
\frac{d(SON\_Stable)}{dt} = N\_Lit\_hum\_stable - N\_Stable\_min
\]

\[
\frac{d(SIN\_Amm)}{dt} = N\_Lit\_dec + N\_Active\_min + N\_Stable\_min + Amm\_depo - N\_uptake\_amm
- Amm\_nitrif - Gas\_NH_3 - Amm\_imob
\]

\[
\frac{d(SIN\_Nit)}{dt} = Amm\_nitrif + Nit\_depo - Nit\_leach - N\_uptake\_nit - Gas\_NO - Gas\_N_2O - Gas\_N_2
\]

In Eqs. (1) – (6), \( t \) refers to the time step of the calculation (day or year). The N fluxes in above equations, including how each is controlled by external environmental factors, are described in detail below. All acronyms are defined in Table 1. All the external driving variables required by TBNC model are limited to climate (daily values of temperature, precipitation and radiation), soil climate (soil temperature, soil water content and soil pH), vegetation types, and soil texture types.

Table 1. Description of all state, influx and efflux variables simulated in TBNC model

| N Pools         | Classification | Symbol     | Definition                                      | Unit   |
|-----------------|----------------|------------|-------------------------------------------------|--------|
| Plant N pool    | Influxes       | \( N\_uptake\_amm \) | Plant N uptake as in ammonium                   | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( N\_uptake\_nit \) | Plant N uptake as in nitrate                    | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( N\_fall\_amm \) | Litter-fall from plant tissues                  | Tg N \cdot yr\(^{-1}\) |
|                 | Effluxes       | \( Veg\_N \) | Organic N storage in plant pool                 | Pg N   |
|                 | Storages       | \( Lig\_N \) | Organic N storage in litter pool                | Pg N   |
| Litter N pool   | Influxes       | \( N\_fall\_amm \) | Litter-fall from plant tissues                  | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( N\_fix \) | Biological N fixation                           | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( N\_Lit\_dec \) | Decomposition from litter                       | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( N\_Lit\_hum\_active \) | Litter huminification for active SON          | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( N\_Lit\_hum\_stable \) | Litter huminification for stable SON          | Tg N \cdot yr\(^{-1}\) |
|                 | Storages       | \( Lig\_N \) | Organic N storage in litter pool                | Pg N   |
| Active SON pool | Influxes       | \( N\_Lit\_hum\_active \) | Litter huminification for active SON          | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( N\_Active\_min \) | Active SON mineralization                      | Tg N \cdot yr\(^{-1}\) |
|                 | Storages       | \( SON\_Active \) | Active humus storage in SON pool               | Pg N   |
| Stable SON pool | Influxes       | \( N\_Lit\_hum\_stable \) | Litter huminification for stable SON          | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( N\_Stable\_min \) | Stable SON mineralization                      | Tg N \cdot yr\(^{-1}\) |
|                 | Storages       | \( SON\_Stable \) | Stable humus storage in SON pool               | Pg N   |
| Ammonium SIN pool | Influxes   | \( N\_Lit\_dec \) | Decomposition from litter                       | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( N\_Active\_min \) | Active SON mineralization                      | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( N\_Stable\_min \) | Stable SON mineralization                      | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( Amm\_depo \) | Ammonium deposition                             | Tg N \cdot yr\(^{-1}\) |
|                 | Effluxes       | \( N\_uptake\_amm \) | N uptake as in ammonium                        | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( Gas\_NH_3 \) | Ammonium volatilization                        | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( Amm\_nitrif \) | Ammonium nitrification                         | Tg N \cdot yr\(^{-1}\) |
|                 | Storages       | \( SIN\_Amm \) | Ammonium storage in SIN pool                   | Pg N   |
| Nitrate SIN pool | Influxes       | \( Amm\_nitrif \) | Ammonium nitrification                         | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( Nit\_depo \) | Nitrate deposition                              | Tg N \cdot yr\(^{-1}\) |
|                 | Effluxes       | \( N\_uptake\_nit \) | N uptake as in nitrate                          | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( Nit\_denitrif \) | Nitrate denitrification                        | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( Nit\_leach \) | Nitrate leaching                                | Tg N \cdot yr\(^{-1}\) |
|                 |                | \( Gas\_NO_X \) | Gaseous losses as in NO_X                      | Tg N \cdot yr\(^{-1}\) |
|                 | Storages       | \( SIN\_Nit \) | Nitrate storage in SIN pool                    | Pg N   |
2.1.3. Model sensitivity analysis

Sensitivity analysis considers the robustness of a model’s results to relatively changes in the main input parameters [20]. In this study, a ‘one-at-a-time’ (OAT) method [21, 22] is used to examine the relative sensitivity of model major input parameters in TBNC model.

For an investigation of the uncertainties in the parameter values, we measure the sensitivity by the response of model output to a fractional change in one single model parameter, while other parameters remained constant. We chose the six major parameters in N pools shown in Table 3, which included maximum theoretical photosynthetically active radiation conversion efficiency ($\varepsilon_{\text{max}}$), decomposition rates of litter ($\tau_1$), mineralization rate of active SON ($\tau_2$), mineralization rate of stable SON ($\tau_3$), maximum rate of ammonium nitrified (Nmax), maximum rate of denitrification (DENmax). Each of the parameters was changed by a magnitude of ±20%, and the sensitivity index (SI) was calculated using the following equation [23]:

$$SI = \frac{[Y(x + \Delta x) - Y(x)] + [Y(x - \Delta x) - Y(x)]}{Y(x)}$$

(7)

Where $x$ is the value of the independent variable, $\Delta x$ is the value for a fractional change of $x$, $Y(x)$ is the value of the dependent variable and $Y(x \pm \Delta x)$ is the corresponding change in $Y(x)$ in response to the change in $x$.

2.1.4. Model validation

To validate a model empirically, one may employ either temporally or spatially independent data [24]. In this study, model estimates were compared with other model results. Since there are obvious variations among different soil layers for N content, it is difficult to achieve comparable observed data of soil organic and inorganic N content. Besides, the site-specific nature of the validation approach has limitations for global patterns and quantities. In doing so, soil C and N density from the Global Gridded Surfaces of Selected Soil Characteristics (IGBP-DIS) dataset [25] were used as spatial reference data for comparing the simulated soil C and N content. Moreover, spatial pattern of plant C content is also compared with the New IPCC Tier-1 global biomass carbon map for the year of 2000 [26].

2.2. Data preparation

For a global scale simulation, a large amount of input data, including climate, soil and land cover data, was required in this study (Table 2). Of these data, meteorological input was from the 10-year daily Global Land Data Assimilation system (GLDAS, 2000-2009) dataset distributed by the Goddard Earth Sciences Data and Information Services Center (GES-DISC). Gridded soil physical parameters were estimated from Harmonized World Soil Database (HWSD, Ver.1.0). Land cover data was obtained from the at-launch MODIS Land Cover Type product with the discrete classifications provided by UMD (MOD12Q1, V004, 2002-2008).

Owing to a large degree of variation in data from sources with different spatial and temporal resolutions, it was necessary to perform a procedure of data reprocessing and standardization. To do this, all meteorological data were converted into binary format data with a cell size of 0.25° in a standard GIS software environment (ESRI, ArcGIS 9.2). In order to capture as much of the global range of variation in land cover and soil characteristics as possible, all the soil and land cover products with spatial resolution of 30” were aggregated to a 0.25°×0.25° grid, while the fractional cover information within each grid cell was preserved. In this way, the global areal coverage of the vegetation types or soil texture types was preserved in the aggregation process, which was not the case when aggregating a discrete classification using whether the nearest neighbour or majority reclass approaches. Additionally, for reducing the time of calculations, the geographical regions absolutely unsuitable for plant growth were masked from the input data in southern regions. The study area covered the globe is from longitude 180° W to 180° E and from latitude 90°N to 60°S.

A global gridded estimates of atmospheric N deposition for the years 1860 and 1993 and projections for the year 2050 are provided by Galloway et al., (2004) [16], which are composed of total inorganic N, NHx (NH3 and NH4+), and NOy (all oxidized forms of N including N2O) with a spatial resolution of 5° × 3.75° [17, 18].

Table 2. Database used in model development and model calculation

---

*Note: The table content is not provided in the image, but it is implied that there is a table related to the database used in model development and model calculation.*
3. Results and Discussions

3.1. The improved TBNC model

3.1.1. Model sensitivity analysis

The sensitivity analysis results showed that the model is insensitive to the main input parameters (Table 3). In particular, the model results appeared to be most sensitive to the rate of litter decomposition ($\tau_1$). This reflects the fact that changes in the N storages are generally related more closely to fluctuations in litter decomposition than other ecological processes. This can probably be attributed to the assumption that the litter decomposition is the main sources for both SON and SIN in a hypothetical natural N cycle. In addition, the model also showed different sensitivities for different N pools. Given the same magnitude of change in input parameters, the ammonium and nitrate SIN pools are more easily influenced than other N pools. This interprets, to some extent, the N fluxes among these pools are more sensitive to the changes in the rates of photosynthesis ($\varepsilon_{\text{max}}$), nitrification (N$_{\text{max}}$) and denitrification (DEN$_{\text{max}}$), since there is only a finite amount of soil inorganic N available for plant uptake in natural ecosystem.
Table 3. Sensitivity analysis of key parameters

| Parameters                   | Plant N pool | Litter N pool | Active SON pool | Stable SON pool | Ammonium SIN pool | Nitrate SIN pool |
|------------------------------|--------------|---------------|-----------------|-----------------|-------------------|-----------------|
|                              | +20%         | -20%          | +20%            | -20%            | +20%              | -20%            |
|                              | SI           | SI            | SI              | SI              | SI                | SI              |
| εmax                        | 7.50         | 7.39          | 0.02            | 26.55           | 26.25             | 0.01            | 11.61           | 12.78           | 0.10             | 1.91            | 2.20            | 0.14             |
| τ1                          | 7.87         | 6.94          | 0.12            | 24.68           | 28.60             | 0.15            | 98.74           | 80.86           | 0.20             | 15.08           | 12.35           | 0.20             | 12.60           | 11.33           | 0.11             | 2.06            | 1.88            | 0.10             |
| τ2                          | 7.54         | 7.38          | 0.02            | 26.52           | 26.34             | 0.01            | 88.64           | 92.79           | 0.05             | 13.87           | 13.83           | 0.00             | 12.14           | 11.93           | 0.02             | 2.04            | 2.03            | 0.01             |
| τ3                          | 7.46         | 7.46          | 0.00            | 26.43           | 26.43             | 0.00            | 90.68           | 90.68           | 0.00             | 13.83           | 13.87           | 0.00             | 12.04           | 12.04           | 0.00             | 2.03            | 2.03            | 0.00             |
| Nmax                        | 7.46         | 7.46          | 0.00            | 26.43           | 26.43             | 0.00            | 90.68           | 90.68           | 0.00             | 13.85           | 13.85           | 0.00             | 11.62           | 12.54           | 0.08             | 2.11            | 1.94            | 0.09             |
| DENmax                      | 7.46         | 7.46          | 0.00            | 26.42           | 26.44             | 0.00            | 90.66           | 90.69           | 0.00             | 13.85           | 13.85           | 0.00             | 12.02           | 12.05           | 0.01             | 1.89            | 2.20            | 0.16             |

*SI, sensitivity index, which is calculated by Eq. (1) (see in text); εmax, maximum theoretical photosynthetically active radiation conversion efficiency (kg C MJ⁻¹ m⁻² day⁻¹); τ, decomposition rates of litter (yr⁻¹); τ, mineralization rate of active SON (yr⁻¹); τ, mineralization rate of stable SON (yr⁻¹); Nmax, maximum rate of ammonium nitrified (kg N m⁻² day⁻¹); DENmax, maximum rate of denitrification (kg N m⁻² day⁻¹).
3.1.2. Model validation

Although simulated global major N storages show similar spatial distribution pattern to those results derived from previous version [19] and DyN [2], quantitative spatial comparison approach was still needed to evaluate the spatial location of major C and N storages. Fig.2-a illustrates the comparison between the simulated spatial distribution of the plant C content and the global biomass carbon map (New IPCC Tier-1). It is obvious that the model estimates largely coincided with the reference data in most temperate and cold regions, where overall differences are less than 10%. The discrepancies between them occurred mainly in some regions of tropical and subtropical area (20%–30%). This difference occurs because the same IPCC default carbon value was applied to all vegetation within each broad class regardless of growth condition [26]. This means that the indicated C storage in a given location could be more or less than the model simulation. As for the comparison between the simulated soil C and N content and the global distribution map of soil C and N density from IGBP-DIS dataset (Fig. 2-b), it is noticeable that global soil N storage shows a similar distribution pattern to soil C storage. In general, the model simulation was much higher than the IGBP-DIS dataset in temperate regions (20%–30%), such as North America, Europe and Southern Russia, and also in some tropical regions (10%–20%), such as Central Africa and South America.

3.2. Potential changes of N storages and fluxes upon the N deposition

The above-verified TBNC model is employed as a modelling approach to simulate future changes of the N storages and fluxes in given N deposition scenarios. The sums of N storages and fluxes in each pool derived as simulated values of model variables for the corresponding N deposition. These simulated results are summarized and compared with estimates using other models (Table 4). According to the balance analysis of the scenarios, the coefficients are found to vary greatly among the six N pools. The maximum and minimum coefficients appear in the stable SON and
plant/litter N pools, respectively. Most of the coefficients are lower than 1% except for that of the stable SON pool, in very good agreement with the result of previous analysis [19]. All the preliminary results have proved the potential effect of future N deposition on the balance of the N cycle.

3.2.1. N storages and fluxes in plant

It can be seen clearly that plant N pool showed no difference in different N depositions. Total N storages in plant is estimated by simulation to be 12.53 Pg, which is between the previous estimates obtained by McElroy et al. (1976; 10 Pg N)[27] and Kimura (1989; 15 Pg N)[28]. Correspondingly, the annual plant N uptake is estimated by simulation to be 3842 Tg N yr\(^{-1}\) as in ammonium and 528 Tg N yr\(^{-1}\) as in nitrate in the scenario of DEPO-I, while minor decrease of ammonium and increase of nitrate with almost same amount are found in DEPO-II. Meanwhile, as a major efflux from the plant N pool, N litter fall occurs at a rate of 4372(± 1) Tg N yr\(^{-1}\), which is nearly the same as the annual flux rate of plant N uptake.

3.2.2. N storages and fluxes in litter

The storage of litter N is estimated by simulation to be 14.14 Pg in both DEPO-I and DEPO-II (Table 3), which is in good agreement with our previous simulation (Lin et al., 2000; 20 Pg) [19] and higher than a previous model estimate by Xu and Prentice (2008; 4.6 Pg) [2]. In addition to litter fall from plant N pool, another important source flux (biological N fixation by soil microorganisms) is simulated to be 368 Tg N yr\(^{-1}\). Regarding the output fluxes from the litter pool, part of the N in the litter is directly decomposed into ammonium at a rate of 2918 Tg N yr\(^{-1}\), and the rest of the N in the litter is converted into humus through the huminification processes occurring in the active SON pool (1809 Tg N yr\(^{-1}\)) and the stable SON pool (12 Tg N yr\(^{-1}\)). In all, Changes of N deposition have no obvious influence on the N fluxes and storages in litter.

3.2.3. N storages and fluxes in SON

The global amount of organic N stored in surface soil is estimated by simulation to be 44.24 Pg in the active SON pool and 7.47 Pg in the stable SON pool, which is also of a similar magnitude to values obtained by simulations of Lin et al. (2000) [19] and Xu and Prentice (2008) [2] (Table 4). It was found that there is only very little increase of both active and slow SON, which indicates that SON is also not affected by the elevated N deposition.

3.2.4. N storages and fluxes in SIN

In contrast to the huge amount of organic N stored in the soil, all the mineral soil N pools (mainly ammonium and nitrate) are quite small, contributing to less than 10% of total soil N. The amount of ammonium and nitrate are estimated by simulation to be 10.36 Pg and 2.01 Pg in DEPO-I, respectively, which are consistent with the estimate of 15 Pg for the amount of inorganic N in surface soil obtained using our previous model [19] but much higher than the results obtained by the DyN model (0.36 Pg ammonium and 0.58 Pg nitrate) [2]. As for DEPO-II, Ammonium and nitrate are estimated to be 11.39 Pg and 2.47 Pg, which are about 10% and 23% higher than those in DEPO-I.

As a response for increase rates of 34% and 77% as in NO\(_2\) and NH\(_3\) depositions, Denitrification showed the greatest rate of change among all the fluxes, which is simulated to be 258 Tg N yr\(^{-1}\) in DEPO-I and 322 Tg N yr\(^{-1}\) in DEPO-II. Moreover, all other N fluxes in the SIN pool, such as ammonium volatilization, nitrate leaching, gaseous losses (mainly N\(_2\)O and NO) and nitrification, are predicted to increase about 10-20% in DEPO-II. The estimates are much higher than the recently predicted global rates [15, 29, 30]. One of the reasons for the difference is that the soil database (soil temperature and moisture) used in this model is different from that used in other models.
Table 4. Comparison of simulated N storages (Pg N), simulated N influxes, and simulated N effluxes (Tg N yr-1) in three scenarios with previous reported values at the global level

| N Pools          | Classification     | Symbol                      | DEPO-I | DEPO-II | Reference values |
|------------------|--------------------|-----------------------------|--------|---------|------------------|
| Plant N pool     | Influxes           | N\textsubscript{uptakeann} | 3842   | 3826    | 412\textsuperscript{[1]}, 4744\textsuperscript{[19]} |
|                  |                    | N\textsubscript{uptakeoff}  | 528    | 547     | 665\textsuperscript{[1]}, 1463\textsuperscript{[19]} |
|                  | Effluxes           | N\textsubscript{fallann}    | 4371   | 4373    | 6274\textsuperscript{[19]} |
|                  |                    | N\textsubscript{fix}        | 368    | 369     | 211\textsuperscript{[19]}, 145\textsuperscript{[1]} |
|                  |                    | N\textsubscript{Lit dec}    | 2918   | 2919    | 3544\textsuperscript{[19]} |
|                  |                    | N\textsubscript{Lit hum}    | 1821   | 1822    | 2839\textsuperscript{[19]} |
|                  | Storage            | Veg N                       | 12.53  | 12.54   | 10\textsuperscript{[21]}, 15\textsuperscript{[28]}, 16\textsuperscript{[19]}, 5.3\textsuperscript{[2]} |
| Coefficients of difference CD | -0.02\%           | 0.00\%                      | -      | -       |                  |
| Litter N pool    | Influxes           | N\textsubscript{fallann}    | 4371   | 4373    | 6274\textsuperscript{[19]} |
|                  |                    | N\textsubscript{fix}        | 368    | 369     | 211\textsuperscript{[19]}, 145\textsuperscript{[1]} |
|                  | Effluxes           | N\textsubscript{Lit dec}    | 2918   | 2919    | 3544\textsuperscript{[19]} |
|                  |                    | N\textsubscript{Lit hum}    | 1821   | 1822    | 2839\textsuperscript{[19]} |
|                  | Storage            | Lit N                       | 14.14  | 14.15   | 20\textsuperscript{[19]}, 4.6\textsuperscript{[2]} |
| Coefficients of difference CD | -0.06\%           | 0.00\%                      | -      | -       |                  |
| Active SON pool  | Influxes           | N\textsubscript{Lit humactive} | 1809  | 1810    | 2695\textsuperscript{[19]} |
|                  | Effluxes           | N\textsubscript{Active min} | 1810   | 1811    | 2695\textsuperscript{[19]} |
|                  | Storage            | SON\textsubscript{Active}   | 44.24  | 44.26   | 56.8\textsuperscript{[2]}, 70\textsuperscript{[32]}, 95\textsuperscript{[11]} |
| Coefficients of difference CD | -0.06\%           | 0.00\%                      | -      | -       |                  |
| Stable SON pool  | Influxes           | N\textsubscript{Lit humstable} | 12    | 12      | 44\textsuperscript{[19]} |
|                  | Effluxes           | N\textsubscript{Stable min} | 11     | 11      | 44\textsuperscript{[19]} |
|                  | Storage            | SON\textsubscript{Stable}   | 7.47   | 7.48    | 12\textsuperscript{[19]} |
| Coefficients of difference CD | 8.33\%            | 8.33\%                      | -      | -       |                  |
| Ammonium SIN pool| Influxes           | N\textsubscript{Lit dec}    | 2918   | 2919    | 3544\textsuperscript{[19]} |
|                  | Effluxes           | N\textsubscript{active min} | 1810   | 1811    | 2695\textsuperscript{[19]} |
|                  | Storage            | Ammon \textsubscript{dep}e  | 133    | 236     | 77\textsuperscript{[19]}, 135\textsuperscript{[14]} |
|                  |                    | Ammon \textsubscript{NH}\textsubscript{3} | 211  | 259     | 34\textsuperscript{[19]} |
|                  |                    | Ammon \textsubscript{nitrif} | 818    | 890     | 805\textsuperscript{[19]} |
|                  | Storage            | Ammon \textsubscript{SIN}   | 10.36  | 11.39   | 10.7\textsuperscript{[19]}, 0.361\textsuperscript{[2]} |
| Coefficients of difference CD | 0.02\%            | 0.04\%                      | -      | -       |                  |
| Nitrate SIN pool | Influxes           | Ammon \textsubscript{nitrif} | 818    | 890     | 805\textsuperscript{[79]} |
|                  | Effluxes           | Nit \textsubscript{depo}    | 112    | 150     | 39\textsuperscript{[9]}, 112\textsuperscript{[14]} |
|                  |                    | Nit\textsubscript{uptakeoff} | 528    | 547     | 661\textsuperscript{[1]}, 1463\textsuperscript{[19]} |
|                  |                    | Nit\textsubscript{denitrif} | 258    | 322     | 240\textsuperscript{[19]}, 124\textsuperscript{[15]}, 280\textsuperscript{[30]} |
|                  |                    | Nit\textsubscript{leach}    | 131    | 157     | 12\textsuperscript{[19]}, 15\textsuperscript{[29]} |
|                  |                    | Gas\textsubscript{NO}\textsubscript{3} | 12    | 14      | 3\textsuperscript{[19]}, 12\textsuperscript{[30]} |
|                  | Storage            | SING\textsubscript{Nit}    | 2.01   | 2.47    | 3.3\textsuperscript{[19]}, 0.58\textsuperscript{[7]} |
| Coefficients of difference CD | 0.11\%            | 0.00\%                      | -      | -       |                  |

4. Concluding remarks

This paper describes an improved modelling approach for simulating dynamically changes in the N cycle resulting from elevated N deposition on a global scale. The basic hypothesis was that all plant, litter, and soil N pools develop along a monotonic path from the zero state to the steady state with only a very small perturbation of the leaf C and N. A steady state model refers to model state variables reaching a dynamical balance or to N influxes into each pool being balanced by effluxes. After imposing anthropogenic disturbances, i.e. future N deposition, on this steady state model, the ‘disturbed’ state of the terrestrial biosphere can be calculated until it again reaches a steady state. The steady state model was used as a tool to quantitatively evaluate anthropogenic disturbances against the background of our quantitative knowledge of the biogeochemical N cycle.

All empirical validations of this model by comparison with other estimates of the N spatial distribution obtained using other models indicate that the updated model is suitable for reliably simulating global amounts and patterns of N fluxes and storages. Moreover, a sensitivity analysis on the uncertainties of the input parameters indicated that the updated model has a more robust structure and allows the convincing simulation of the behaviours and properties of the natural N cycle. Nevertheless, although it is necessary to future validate model results and consider the interaction mechanisms of gaseous NO, N\textsubscript{2}O, and CH\textsubscript{4} emissions, the current TBNC model is expected to be a useful tool for quantifying environmental loads in the terrestrial ecosystem that are calculated as the responses of N cycling to changes in the global N budget, particularly direct changes through industrial and agricultural activities and indirect changes through fossil fuel use and changes in climate and land cover.

The model still contains some limitations and uncertainties. First, when the model are used to simulate composition and distribution of N reservoirs and fluxes, the fixed model parameters, i.e. the predefined N ecosystem retention
efficiency, the allocation logic among plant tissues and C:N ratios in various ecosystems, etc., should be in a dynamic state and change spatially and temporally, and all these inherent uncertainties can bring about some bias in the model outputs. Second, since N cycling are so dynamic and mechanistic understanding of C-N-climate interactions is insufficient [1], even when all the model parameters is well optimized according to the environment conditions, realistic spatiotemporal pattern of N cycle may not necessarily be described by those empirical relationships derived from field observations that operate at finer spatiotemporal scales. Third, one of the reasons for the difference between the model estimates and the IGEP-DIS dataset is that the database was produced from the statistical data in the 1990s, and it describes the soil C and N density at a depth interval of 0–100 cm, which is less than the soil depth used in this study (0–150 cm). Uncertainties or bias in the reference data can distort the performance of the model validation in some way.

Acknowledgements

The research described in this paper was supported and financed by the National Basic Research Program of China (973 Program, No. 2010CB951502), and by the Natural Science Foundation of China (No.40930101), and by the Ministry of Finance of China through Non-profit National Research Institute (IARRP-2011-015), and by the funding of the New Energy and Industrial Technology Development Organization (NEDO) of Japan. All persons and institutes who kindly made their data available for this analysis are acknowledged.

References

[1] Gruber N, Galloway JN. An earth-system perspective of the global nitrogen cycle. Nature 2008; 451: 293–6.
[2] Xu R, Prentice IC. Terrestrial nitrogen cycle simulation with a dynamic global vegetation model. Global Change Biol 2008; 14: 1745–64.
[3] Li CS, Frolking S, Frolking TA. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. J Geophys Res 1992; 7: 9759–76.
[4] Raich JW, Rastetter EB, Melillo JM, Kicklighter DW, Steudler PA, Peterson BJ. Potential net primary productivity in South America: application of a global model. Ecol Appl 1991; 1: 399–429.
[5] McGuire AD, Melillo JM, Joyce LA, Kicklighter DW, Grace AL, Moore IIIB, et al. Interactions between carbon and nitrogen dynamics in estimating net primary productivity for potential vegetation in North America. Glob Biogeochem Cycles 1992; 6: 101–24.
[6] Friend AD, Stevens AK, Knox RG, Cannell MGR. A process-based, terrestrial biosphere model of ecosystem dynamics (Hybrid 3.0). Ecol Model 1997; 95: 249–87.
[7] Wang W, Ichii K, Hashimoto H, Michaelis AR, Thornton PE, Law BE, et al. A hierarchical analysis of terrestrial ecosystem model Biome–BGC: Equilibrium analysis and model calibration. Ecol Model 2009; 220: 2009–23.
[8] Melillo JM. Human influences on the global nitrogen budget and their implications for the global carbon budget. In: Munai, S, Kimuar, M. (Eds.), Toward Global Planning of Sustainable Use of the Earth: Development of Global Eco-Engineering, New York: Elsevier; 1995, p. 117–34.
[9] Lin BL, Sakoda A, Shibasaki R, Suzuki M. A modelling approach to global nitrate leaching caused by anthropogenic fertilization. Water Res 2001; 35: 1961–8.
[10] Burns RC, Hardy RWF. Nitrogen Fixation in Bacteria and Higher Plants. New York: Springer-Verlag; 1975.
[11] Levy H, Moxim WJ. Simulated global distribution and deposition of reactive nitrogen emitted by fossil fuel combustion. Tellus 1989; B41: 256–71.
[12] FAO. Global inventory of NH3 emissions from mineral fertilizers and animal manure applied to croplands and grasslands, by Bouwman AF. Rome; 2001.
[13] Holland EA. Variations in the predicted spatial distribution of atmospheric nitrogen deposition and their impact on carbon uptake by terrestrial ecosystems. J Geophys Res-Oceans 1997; 102: 15849–66.
[14] Houghton RA, Davidson EA, Woodwell GM. Missing sinks, feedbacks, and understanding the role of terrestrial ecosystems in the global carbon balance. Global Biogeochem Cycles 1998; 12(1): 25–34.
[15] Schlesinger WJ. On the fate of anthropogenic nitrogen. PNAS 2009; 106: 203–8.
[16] Galloway JN, Dentener FJ, Capone DG, Boyer EW, Howarth RW, Seitzinger SP, et al. Nitrogen cycles: past, present and future. Biogeochemistry 2004; 70: 153–226.
[17] Jeukens AP, Veekind F, Dentener F, Metzger S, Robles-Gonzalez C. Simulation of the aerosol optical depth over Europe for August 1997 and a comparison with observations. J Geophys Res 2001; 106: 28295–311.
[18] Lelieveld J, Dentener F. What controls tropospheric ozone? J Geophys Res 2000; 105: 3531–51.
[19] Lin BL, Sakoda A, Shibasaki R, Goto N, Suzuki M. Modelling a global biogeochemical nitrogen cycle in terrestrial ecosystems. Ecol Model 2000; 135: 89–110.

[20] Snowling SD, Kramer JR. Evaluating modelling uncertainty for model selection. Ecol Model 2001; 138: 17–30.

[21] Cariboni J, Gatelli D, Liska R, Saltelli A. The role of sensitivity analysis in ecological modelling. Ecol. Model 2007; 203: 167–82.

[22] Wu WB, Shibasaki R, Yang P, Tan GX, Matsumura KI, Sugimoto K. Global–scale modeling of future changes in sown areas of major crops. Ecol Model 2007; 208: 378–90.

[23] Vanlooster M, Viaene P, Diels J, Feyen J. A deterministic evaluation analysis applied to an integrated soil–crop model. Ecol Model 1995; 81: 183–95.

[24] Pontius RG, Jr, Huffaker D, Denman K. Useful techniques of validation for spatially explicit land–change models. Ecol Model 2004; 179: 445–61.

[25] Global Soil Data Task Group. Global Gridded Surfaces of Selected Soil Characteristics (IGBP-DIS). Global Gridded Surfaces of Selected Soil Characteristics Dataset. Available online [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A; 2000.

[26] Ruesch, Aaron, Holly K. Gibbs. New IPCC Tier-1 Global Biomass Carbon Map for the Year 2000. Available online [http://cdiac.ornl.gov], Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A; 2008.

[27] McElroy MB, Elkins JW, Wofsy SC, Yung YL. Sources and sinks for atmospheric N,O. Rev Geo Space Phys 1976; 14 (2), 143–50.

[28] Kimura M. Effects of soil organisms on the elemental cycle in soil, Ch. 10. In: Japanese Chemical Society (Eds.), Kikan Kagaku Sosetsu (in Japanese), vol. 4, Japanese Chemical Society, Japan; 1989, p.129–54.

[29] Seitzinger S, Harrison JA, Böhle JK, Bouwman AF, Lowrance R, Peterson B, et al. Denitrification across landscapes and watersheds. Ecol Appl 2006; 16: 2064–90.

[30] Galloway JN, Townsend AR, Erisman JW, Bekunda M, Cai Z, Freney JR, et al. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science 2008; 320: 889–92.

[31] Melillo JM, McGuire AD, Kicklighter DW, Moore IIIB, Vorosmarty CJ, Schloss AL. Global climate change and terrestrial net primary production. Nature 1993; 363: 234–40.

[32] McElroy M. Global Change: A Biogeochemical Perspective, JPL–Publishers; 1983

[33] Post WM, Pastor J, Zinke PJ, Stangenberger AG. Global patterns of soil nitrogen storage. Nature 1985; 317: 613–6.

[34] Dentener F, Drevet J, Lamarque JE, Bey I, Eichkout B, Fiore AM, et al. Nitrogen and sulphur deposition on regional and global scales: a multi-model evaluation, Glob Biogeochem Cycles 2006; 20: GB4003.