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Designing a Regional Nitrogen Cycle Module of Grassland for the IAP-N Model

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ABSTRACT

Assessment of the nitrogen (N) balance and its long-term trend is necessary for management practices because of the negative environmental effects caused by an imbalance of reactive N in grassland ecosystems. In this study, we designed a module for the IAP-N (Improving Anthropogenic Practices of managing reactive Nitrogen) model to enable it to assess the N budget of regional grasslands. The module was developed to quantify the individual components of the N inputs and outputs for grassland ecosystems using livestock and human populations, grassland area, and fossil-energy consumption data as the model inputs. In this paper, the estimation approaches for individual components of N budget, data acquisition, and parameter selection are described in detail. The model was applied to assess the N budget of Inner Mongolia in 2006 at the county scale. The simulation results show that the most important pathway of N outputs from the grassland was livestock intake. The N output from livestock intake was especially large in the middle of Inner Mongolia. Biological fixation, atmospheric deposition, and livestock excreta deposition were comparably important for the N inputs into the grassland. The N budget for Inner Mongolia grassland in 2006 was $-1.7\times10^8\pm0.6\times10^8$ kg. The case study for Inner Mongolia shows that the new grassland module for the IAP-N model can capture the characteristics of the N budget in a semiarid grassland.

Key words: nitrogen budget, grassland, module, example simulation

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1. Introduction

Grassland ecosystems play a special role in maintaining the structure, functions, and ecological processes in natural ecosystems, especially in ecologically fragile areas, such as arid and semiarid regions, where a number of ecological problems are becoming more serious because of grassland degradation (e.g., Zhao et al., 2004). Like other terrestrial ecosystems, grassland productivity is controlled by nitrogen (N) availability (Vitousek et al., 2002). The reactive N balance in grasslands is essential for sustainability of this ecosystem. The balance is usually determined by inputs through biological fixation, atmospheric deposition, excreta, and fertilization as well as outputs through the release of nitrogenous gases, such as nitrous oxide (N_2O), ammonia (NH_3), nitric oxide (NO), and N_2, removal of hay and livestock products, and possible losses due to wind erosion, surface runoff, and leaching. The gas releases might contribute not only to the N deficit of a grassland ecosystem but also may affect the climate and the atmosphere (Bolle et al., 1986; IPCC, 2001, 2007; Heeb et al., 2006). N deficit in a grassland ecosystem results from greater N outputs than inputs. Long-term deficiencies of this essential nutrient may lead to grassland degradation and may reduce productivity. On the other hand, if inputs of reactive N into a grassland ecosystem are greater than the outputs over the long term, N may accumulate and exert cascading negative effects, such as biodiversity reduction and eutrophication (e.g., Galloway et al., 2004). Therefore, assessment of the N balance and its long-term trend is necessary for developing strategy for management practices to maintain the productivity and ecological function of regional grassland ecosystems.

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Galloway et al. (2004) contrasted the natural and anthropogenic controls on the conversion of unreactive N_2 to more reactive forms of nitrogen (N_r). Regional N budgets for Asia, North America, and other major regions for the early 1990s, as well as the marine N budget, are presented to highlight the dominant N fluxes in each region. Two important findings are that human activities increasingly dominate the N budget at the global and at most regional scales and that the fixed forms of N are accumulating in most environmental reservoirs. The N budget at regional scales had been assessed according to the site experiments. Within the framework of NitroEurope projects, Ammann et al. (2009) measured N exchange on the field scale at the grassland site Oensingen. The N budget of the managed grassland was more complex. In addition to the management related import and export, gaseous exchange in many different forms (e.g., NO, NO_2, HNO_3, N_2O, NH_3, and N_2), as well as input by rain and leaching of N-compounds with the soil water, had been measured. Beier et al. (2009) presented N balances of six shrublands along a climatic gradient across the European continent. Nitrogen storage was also dominated by the soil pools, generally showing small losses except when atmospheric N input was high. As an important greenhouse gas (GHG) in the N cycle, nitrous oxide (N_2O) budgets at different regions were estimated. The United Nations Framework Convention on Climate Change (UNFCCC) establish a national emission inventory that fully reports all anthropogenic sources of GHGs, and protocols have been developed by the Intergovernmental Panel on Climate Change (IPCC) that provide a methodology for calculating emissions. Nitrous oxide emission from UK agriculture was estimated, using the IPCC default values of all emission factors and parameters. The advantages of the IPCC method are its simplicity, global coverage, transparency, and use of readily available information. Using country-specific emission factors, these estimates could be improved without substantially altering the framework (Brown et al., 2001). Freibauer (2003) developed a detailed methodology compatible with the guidelines of the IPCC to assess the annual direct biogenic emissions of GHGs released from European agriculture.

Grassland is the largest terrestrial ecosystem in China, with a total area of 3.9×10^8 hm^2, which accounts for 41% of the national land area (Zhao et al., 2004). Inner Mongolia is one of most important pasturing areas in the country, where grassland covers an area of 0.788×10^8 hm^2 (Meng, 1993). So far, however, no assessment on the reactive N balance for grassland is available for the pasture regions of either Inner Mongolia or for other regions of the country. This situation may be partially attributed to a lack of tools or approaches for this type of assessment. Zheng et al. (2002, 2008) developed a simple model, IAP-N (Improving Anthropogenic Practices of managing reactive Nitrogen), as a tool for assessing the N balance in agricultural systems. However, the processes in grassland ecosystems were missing from the IAP-N model. We designed a module for this model to enable the simulation of reactive N budgets in regional grassland ecosystems. In this paper, we describe the details of this module and then exemplify its application for N balance assessment on the regional grassland in Inner Mongolia.

2. Model description

The new grassland module for the IAP-N model was designed to quantify the individual components of N inputs and outputs using livestock and human populations, grassland area and fossil-energy consumption data as the model inputs. As the conceptual structure demonstrates, this module simulates N flows among three major N reservoirs, including the soil–plant pool, the livestock and human pool, and the atmosphere pool (Fig. 1). Inputs into the soil–plant pool of the grassland include biological N fixation, atmospheric N deposition, and N addition from livestock excreta. There are three major N flows out of this pool: the livestock intake of grass/hay, emission of N gases, and nitrate leaching. The livestock/human pool loses N mainly through gas emissions from excreta and the removal of livestock products for commercial purposes. Within the livestock/human pool, reactive N flows among four subpools: livestock, animal products, humans, and excreta from both livestock and humans. The N uptake by livestock from feed (e.g., grass or hay) is allocated into animal products (e.g., meat, milk, and fur) and manure wastes (e.g., urea, feces, and feed residues). A part of the animal product is sold out of the region, while the remaining product is consumed by the local people. The N intake by the local people is excreted to the local environment. Part of the human- and animal-excreted N is released to the atmosphere through gas losses from direct emissions or from manure burning. The remaining excreta are returned to the fold, a portion of which leached out of the livestock/human pool. All parameters used in the equations are evaluated in Appendix A. The calculation procedures were programmed using FORTRAN 95 (Compaq, USA). More details of this module are described in the following subsections.

2.1 *N outputs from the grassland* (*soil–plant system*)

N_out (N outputs from the grassland, $\mathrm{kg\,N\,yr^{-1}}$)

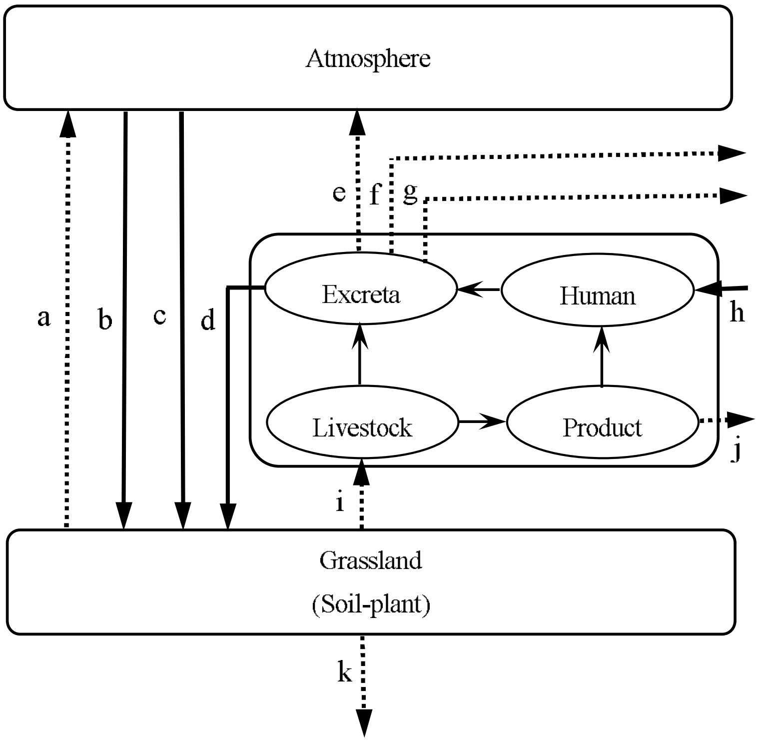

Fig. 1. Conceptual structure of the regional N cycle module of grassland for the IAP-N model: (a) N flow off grassland by gas emissions; (b) N flow into grassland by atmosphere deposition; (c) N flow into grassland by biological fixation; (d) N flow into grassland by livestock excreta; (e) N loss from excreta by gas emissions; (f) N loss from excreta by leaching in fold; (g) N input into fold by livestock and human excreta; (h) N acquisition from other systems by human food; (i) N flow off grassland by livestock intake; (j) N loss by livestock product export; and (k) N flow off grassland by leaching/runoff.

were calculated using Eq. (1). N_livestock, N_gas_grassland, and N_leaching represent the N flow off the grassland by livestock intake (kg N yr^{-1}), the N flow off the grassland by gas emissions (kg N yr^{-1}), and the N flow off the grassland by leaching/runoff (kg N yr^{-1}), respectively:

$$\begin{aligned} \mathrm{N\_out} = {} & \mathrm{N\_livestock} + \mathrm{N\_gas\_grassland} + \\ & \mathrm{N\_leaching}\,. \end{aligned} \tag{1}$$

Livestock in grassland feed on grass; therefore, N_livestock can be estimated by the livestock population in the grassland, annual livestock feed intake, and aboveground N content of the grassland community. Eq. (2) was used to calculate N_livestock:

$$\begin{aligned} \mathrm{N\_livestock} = {} & \mathrm{sheep} \times \mathrm{sheep\_take} \times \mathrm{N\_grass} + \\ & \mathrm{cattle} \times \mathrm{cattle\_take} \times \mathrm{N\_grass} + \\ & \mathrm{horse} \times \mathrm{horse\_take} \times \mathrm{N\_grass}\,, \end{aligned} \tag{2}$$

where sheep, cattle, and horse indicate population, respectively. N_grass represents the aboveground N content for the grassland community (kg kg^{-1}). The annual livestock feed intake includes sheep_intake (i.e., sheep feed intake, kg $sheep^{-1}$ yr^{-1}), cattle_intake (i.e., cattle feed intake, kg $cattle^{-1}$ yr^{-1}), and horse_intake (i.e., horse feed intake, kg $horse^{-1}$ yr^{-1}).

N_gas_grassland was calculated using Eq. (3). N_2O_grassland (i.e., N_2O emissions from grassland, kg N yr^{-1}), NO_grassland (i.e., NO emissions from grassland, kg N yr^{-1}), and N_2_grassland (i.e., N_2 emissions from grassland, kg N yr^{-1}), was estimated by multiplying Area (i.e., the grassland area, hm^2) by EF_N_2O (i.e., N_2O emission factor for grassland, kg N hm^{-2} yr^{-1}), EF_NO (i.e., NO emission factor for grassland, kg N hm^{-2} yr^{-1}), and EF_N_2 (i.e., N_2 emission factor for grassland, kg N hm^{-2} yr^{-1}), respectively:

$$\begin{aligned} \mathrm{N\_gas\_grassland} = {} & \mathrm{N_2O\_grassland} + \\ & \mathrm{NO\_grassland} + \\ & \mathrm{NH_3\_grassland} + \\ & \mathrm{N_2\_grassland}\,, \end{aligned} \tag{3}$$

$$\mathrm{N_2O\_grassland} = \mathrm{Area} \times \mathrm{EF\_N_2O}\,, \tag{4}$$

$$\mathrm{NO\_grassland} = \mathrm{Area} \times \mathrm{EF\_NO}\ , \qquad (5)$$

$$\mathrm{N_2\_grassland} = \mathrm{Area} \times \mathrm{EF\_N_2}\ , \qquad (6)$$

NH_3_grassland values (i.e., NH_3 emissions from grassland, kg N yr^{-1}) were calculated using N_manure (i.e., N from livestock excreta, kg N yr^{-1}), r_grz (a partitioning factor for livestock excreta in grassland), and f_NH_3_grz (an NH_3 emission factor from livestock excreta in grassland, kg kg^{-1}):

$$\mathrm{NH_3\_grassland} = \mathrm{N\_manure} \times \mathrm{r\_grz} \times \mathrm{f\_NH_3\_grz}\ . \qquad (7)$$

N_manure was calculated using N in excreta per sheep (kg N $sheep^{-1}$ yr^{-1}), N in excreta per cattle (kg N $cattle^{-1}$ yr^{-1}), and N in excreta per horse (kg N $horse^{-1}$ yr^{-1}) are f_sheep, f_cattle, and f_horse, respectively:

$$\mathrm{N\_manure} = \mathrm{sheep} \times \mathrm{f\_sheep} + \mathrm{cattle} \times \mathrm{f\_cattle} + \mathrm{horse} \times \mathrm{f\_horse}\ . \qquad (8)$$

N_leaching seldom occurs except in animal manure patches because of the arid conditions in Inner Mongolia grasslands. The amount of nitrate leached below a grazed grass sward was 5.6 times greater than that leached below a comparable cut sward due to a large amount of dissoluble N in animal manure (Ryden et al., 1984). So N_leaching was estimated using N_manure, r_grz, and f_leaching (i.e., N loss factor for grazing livestock excreta by leaching):

$$\mathrm{N\_leaching} = \mathrm{N\_manure} \times \mathrm{r\_grz} \times \mathrm{f\_leaching}\ . \qquad (9)$$

2.2 *N inputs into the grassland* (*soil-plant system*)

N_in (i.e., N inputs into the grassland, kg N yr^{-1}) includes N_bn (i.e., N flow into the grassland by biological fixation, kg N yr^{-1}), N_deposit (i.e., N flow into the grassland by atmospheric deposition, kg N yr^{-1}), and N_manure_inG (i.e., N flow into the grassland by livestock excreta, kg N yr^{-1}; Eq. 10). The grassland area multiplied by f_bn (i.e., biological N fixation factor, kg hm^{-2}) equals N_bn (Eq. 11):

$$\mathrm{N\_in} = \mathrm{N\_bn} + \mathrm{N\_deposit} + \mathrm{N\_manure\_inG}\ , \qquad (10)$$

$$\mathrm{N\_bn} = \mathrm{Area} \times \mathrm{f\_bn}\ . \qquad (11)$$

The sum of NH_3_GE (i.e., NH_3 emissions from the grassland ecosystem, kg N yr^{-1}), NO_x_GE (i.e., NO_x emissions from the grassland ecosystem, kg N yr^{-1}), NO_x_E (i.e., NO_x deposition from energy consumption, kg N yr^{-1}), and N_lightning (i.e., N input by lightning fixation, kg N yr^{-1}) equals N_deposit (Eq. 12). NH_3_grassland, NH_3_fold (i.e., NH_3 emissions from the livestock fold, kg N yr^{-1}), NH_3_burn (i.e., NH_3 emissions from manure burning, kg N yr^{-1}), and NH_3_human (i.e., NH_3 emissions from human excreta, kg N yr^{-1}) were estimated first to estimate NH_3_GE (Eq. 13). Also calculation of NO_x_GE requires estimates of NO_grassland, NO_fold (i.e., NO emissions from the livestock fold, kg N yr^{-1}), NO_x_burn (i.e., NO_x emissions from manure burning, kg N yr^{-1}), and NO_human (i.e., NO emissions from human excreta, kg N yr^{-1}):

$$\mathrm{N\_deposit} = \mathrm{NO_{\mathit{x}}\_GE} + \mathrm{NH_3\_GE} + \mathrm{NO_{\mathit{x}}\_E} + \mathrm{N\_lightening}\ , \qquad (12)$$

$$\mathrm{NH_3\_GE} = \mathrm{NH_3\_grassland} + \mathrm{NH_3\_fold} + \mathrm{NH_3\_burn} + \mathrm{NH_3\_human}\ , \qquad (13)$$

$$\mathrm{NO_{\mathit{x}}\_GE} = \mathrm{NO\_grassland} + \mathrm{NO\_fold} + \mathrm{NO_{\mathit{x}}\_burn} + \mathrm{NO\_human}\ . \qquad (14)$$

NH_3_fold was estimated by N_manure, r_fold (a partitioning factor for grazing livestock excreta in fold), and f_NH_3_fold (an NH_3 emission factor for livestock excreta in fold, kg kg^{-1}; Eq. 15). NO_fold was also calculated using the same method (Eq. 16). The NO emission factor for livestock excreta in fold (kg kg^{-1}) is f_NO _fold:

$$\mathrm{NH_3\_fold} = \mathrm{N\_manure} \times \mathrm{r\_fold} \times \mathrm{f\_NH_3\_fold} \qquad (15)$$

$$\mathrm{NO\_fold} = \mathrm{N\_manure} \times \mathrm{r\_fold} \times \mathrm{f\_NO\_fold} \qquad (16)$$

NH_3_burn were estimated by multiplying N_burn (i.e., N in burned manure as fuel, kg N yr^{-1}) and f_NH_3_burn (an NH_3 emission factor for livestock excreta burning, kg kg^{-1}; Eq. 17). NO_x_burn values were also estimated using this method (Eq. 18). The NO_x emission factor for livestock manure burning (kg kg^{-1}) is f_NO_x_burn. N_burn was calculated by subtracting the N_manure in fold from the N gas emissions and leaching (Eq. 19). The N_2O emission factor for livestock excreta in fold (kg kg^{-1}) and the N_2 emission factor for livestock excreta in fold (kg kg^{-1}) are f_N_2O_fold and f_N_2_fold, respectively. The N loss factor for fold livestock excreta by leaching is f_fold_leaching.

$$\mathrm{NH_3\_burn} = \mathrm{N\_burn} \times \mathrm{f\_NH_3\_burn}\ , \qquad (17)$$

$$\mathrm{NO_{\mathit{x}}\_burn} = \mathrm{N\_burn} \times \mathrm{f\_NO_{\mathit{x}}\_burn}\ , \qquad (18)$$

$$\mathrm{N\_burn} = \mathrm{N\_manure} \times \mathrm{r\_fold} \times (1 - \mathrm{f\_N_2O\_fold} - \mathrm{f\_N_2\_fold} - \mathrm{f\_NH_3\_fold} - \mathrm{f\_NO\_fold} - \mathrm{f\_fold\_leaching})\ . \qquad (19)$$

NH_3_human or NO_human were estimated by multiplying N_human (i.e., N excreted by humans, kg N yr^{-1}) by f_NH_3 or f_NO (i.e., NH_3 or NO emission factors for human excreta that remained after leaching/runoff, kg kg^{-1}). N_human was calculated by multiplying human_population (i.e., human population), f_human (i.e., N excretion rate of human, kg person^{-1} yr^{-1}), and f1 (a partitioning factor for the remaining human excreta after leaching/runoff):

$$\mathrm{NH_3\_human} = \mathrm{N\_human} \times \mathrm{f\_NH_3}\ , \tag{20}$$

$$\mathrm{NO\_human} = \mathrm{N\_human} \times \mathrm{f\_NO}\ , \tag{21}$$

$$\mathrm{N\_human} = \mathrm{human\_population} \times \mathrm{f\_human} \times \mathrm{f1}\ . \tag{22}$$

The fossil energy consumption, which impacts NO$_x$ emissions and deposition, includes petroleum and coal. The coal and petroleum NO$_x$ emissions multiplied by f_deposition (i.e., the proportion of NO$_x$ deposited to land from combustion emissions) equals NO$_x$_E (Eq. 23). Coal and petroleum represent coal consumption (10^3 kg) and petroleum consumption (10^3 kg), respectively. EF_C and EF_P represent the NO$_x$ emission factor of coal consumption in all industry uses [kg N (10^3 kg)$^{-1}$], and the NO$_x$ emission factor of petroleum consumption in all industry uses [kg N (10^3 kg)$^{-1}$].

$$\mathrm{NO}_x\mathrm{\_E} = (\mathrm{Coal} \times \mathrm{EF\_C} + \mathrm{Petroleum} \times \mathrm{EF\_P}) \times \mathrm{f\_deposition}\ . \tag{23}$$

The estimated rate of N$_2$ fixation by lightning is small relative to biological N$_2$ fixation but may be important for ecosystems that lack other important N sources (Galloway et al., 2004). N_lightning was estimated by multiplying Area and f_lightning (grassland area by a factor for N$_2$ fixation by lightning over grassland, kg hm^{-2}):

$$\mathrm{N\_lightning} = \mathrm{Area} \times \mathrm{f\_lightning}\ . \tag{24}$$

N_manure_inG equals N_manure in grassland minus N gas emissions and N leaching (Eq. 25). In Eq. (27), f_N$_2$O_grz, f_NO_grz, and f_N$_2$_grz represent the N$_2$O emission factor for livestock excreta in grassland (kg kg^{-1}), NO emission factor for livestock excreta in grassland (kg kg^{-1}), and the N$_2$ emission factor for livestock excreta in grassland (kg kg^{-1}), respectively:

$$\mathrm{N\_manure\_inG} = \mathrm{N\_manure} \times \mathrm{r\_grz} \times (1 - \mathrm{f\_N_2O\_grz} - \mathrm{f\_NH_3\_grz} - \mathrm{f\_NO\_grz} - \mathrm{f\_N_2\_grz} - \mathrm{f\_leaching})\ . \tag{25}$$

2.3 *N budget for the grassland* (*soil–plant system*)

We obtained N_budget (i.e., N budget for the grassland, kg N yr^{-1}) based on N_in minus N_out:

$$\mathrm{N\_budget} = \mathrm{N\_in} - \mathrm{N\_out}\ . \tag{26}$$

2.4 *N cycle of the livestock/human pool*

N_gas_fold (i.e., N gas emissions from excreta in fold, kg N yr^{-1}) was calculated as the summation of N$_2$O, NH$_3$, NO$_x$ and N$_2$ emissions from the livestock fold, manure burning, and human excreta:

$$\begin{aligned}\mathrm{N\_gas\_fold} = {} & \mathrm{N_2O\_fold} + \mathrm{NH_3\_fold} + \mathrm{NO\_fold} + \mathrm{N_2\ \_fold} + \mathrm{N_2O\_burn} + \mathrm{NH_3\_burn} + {} \\ & \mathrm{NO}_x\mathrm{\_burn} + \mathrm{N_2\ \_burn} + \mathrm{N_2O\_human} + \mathrm{NH_3\_human} + \mathrm{NO\_human} + \mathrm{N_2\ \_human}\ .\end{aligned} \tag{27}$$

NH$_3$ and NO$_x$ emissions from the three sources were described in section 2.2. N$_2$O_fold (N$_2$O emissions from the livestock fold, kg N yr^{-1}) were estimated using N_manure, r_fold (a partitioning factor for grazing livestock excreta in fold), and f_N$_2$O_fold (Eq. 28). N$_2$_fold (N$_2$ emissions from the livestock fold, kg N yr^{-1}) were also calculated using the same method:

$$\mathrm{N_2O\_fold} = \mathrm{N\_manure} \times \mathrm{r\_fold} \times \mathrm{f\_N_2O\_fold}\ , \tag{28}$$

$$\mathrm{N_2\_fold} = \mathrm{N\_manure} \times \mathrm{r\_fold} \times \mathrm{f\_N_2\_fold}\ . \tag{29}$$

N$_2$O_burn (N$_2$O emissions from manure burning, kg N yr^{-1}) was estimated by multiplying N_burn and f_N$_2$O_burn (i.e., N$_2$O emission factors for livestock excreta burning, kg kg^{-1}) (Eq. 30). N$_2$_burn (i.e., N$_2$ emissions from manure burning, kg N yr^{-1}) were also estimated using this method. The N$_2$ emission factor for livestock manure burning (kg kg^{-1}) is f_N$_2$_burn:

$$\mathrm{N_2O\_burn} = \mathrm{N\_burn} \times \mathrm{f\_N_2O\_burn}\ , \tag{30}$$

$$\mathrm{N_2\_burn} = \mathrm{N\_burn} \times \mathrm{f\_N_2\_burn}\ . \tag{31}$$

N$_2$O_human and N$_2$_human (N$_2$O and N$_2$ emissions from human excreta, kg N yr^{-1}) were estimated by multiplying N_human by f_N$_2$O and f_N$_2$ (N$_2$O or N$_2$ emission factors for human excreta remaining after leaching/runoff, kg kg^{-1}), respectively:

$$\mathrm{N_2O\_human} = \mathrm{N\_human} \times \mathrm{f\_N_2O}\ , \tag{32}$$

$$\mathrm{N_2\_human} = \mathrm{N\_human} \times \mathrm{f\_N_2}\ . \tag{33}$$

N_fold_leaching (i.e., N leaching from the fold, kg N yr^{-1}) arises from N manure in the livestock fold and human excreta. One can be estimated using N_manure, r_fold and f_fold_leaching; the other is calculated by multiplying the human_population, f_human, and N loss rate (1 − f1):

$$\mathrm{N\_fold\_leaching} = \mathrm{N\_manure} \times \mathrm{r\_fold} \times \mathrm{f\_fold\_leaching} + \mathrm{human\_population} \times \mathrm{f\_human} \times (1 - \mathrm{f1})\ . \tag{34}$$

N_manure_in F (i.e., N flow into the fold by livestock and human excreta, kg N yr^{-1}) has two parts. One part is N_manure in the livestock fold minus the N gas emissions, while the second is N_human minus the N gas emissions:

$$\begin{aligned}\text{N\_manure\_inF} = {} & \text{N\_manure} \times \text{r\_fold} \times [1- \\ & (\text{f\_N}_2\text{O\_fold} + \text{f\_NH}_3\text{\_fold} + \\ & \text{f\_NO\_fold} + \text{f\_N}_2\text{\_fold})] + \\ & (\text{human\_population} \times \\ & \text{f\_human} - \text{N}_2\text{O\_human} - \\ & \text{NH}_3\text{\_human} - \text{NO\_human} - \\ & \text{N}_2\text{\_human})\,. \end{aligned} \tag{35}$$

Cereal and vegetables are major human foods coming from outside the grassland ecosystem. The N content is very low in vegetables; therefore, the major N source from outside the grassland ecosystem is from N in cereal consumed by humans. N_human_in (N acquisition from other systems by human food, kg N yr^{-1}) can be estimated by multiplying human_population, human_cereal (cereal consumption rate, kg $person^{-1}$), and cereal_N (N content in cereal):

$$\begin{aligned}\text{N\_human\_in} = {} & \text{human\_population} \times \\ & \text{human\_cereal} \times \text{cereal\_N}\,. \end{aligned} \tag{36}$$

The N_product (i.e., N exported as livestock product to other systems, kg N yr^{-1}) was estimated using the amount of livestock products minus the portion of products that are consumed by local people. In Eq. (37) sheep_meat (i.e., sheep meat product, kg), cattle_meat (i.e., cattle meat product, kg), and livestock_milk (i.e., livestock milk product, kg) are needed. N content in meat and N content in milk are meat_N and milk_N. In addition, human_meat (i.e., meat consumption rate, kg $person^{-1}$) and human_milk (milk consumption rate, kg $person^{-1}$) are essential:

$$\begin{aligned}\text{N\_product} = {} & (\text{sheep\_meat} + \text{cattle\_meat}) \times \\ & \text{meat\_N} + \text{livestock\_milk} \times \\ & \text{milk\_N} - \text{human\_population} \times \\ & \text{human\_meat} \times \text{meat\_N} - \\ & \text{human\_population} \times \\ & \text{human\_milk} \times \text{milk\_N}\,. \end{aligned} \tag{37}$$

For the livestock/human pool, N_livestock and N_human_in are the N sources. N_product, N excreted by humans, and N_manure are the components of N loss from the livestock/human pool. N_budget_P (livestock/human N budget, kg N yr^{-1}) can be estimated by the subtracting the N loss from the N sources (Eq. 38). The value of the N_budget_P is the net N income needed to maintain local humans and livestock.

$$\begin{aligned}\text{N\_budget\_P} = {} & \text{N\_livestock} + \text{N\_human\_in} - \\ & \text{N\_product} - \text{human\_population} \times \\ & \text{f\_human - N\_manure}\,. \end{aligned} \tag{38}$$

3. Case application of the new IAP-N module in Inner Mongolia

3.1 *Preparation of data to drive the model simulation*

The livestock populations were acquired from county statistics. The annual sheep and cattle populations in the grassland included two parts: the population of the extant livestock at the end of the year and the population out of fold. The extant sheep and cattle population data at the end of the year were acquired from the *Inner Mongolia Statistical Yearbook* (*IMSY*, Statistical Bureau of Inner Mongolia Autonomous Region, 2007), and from the Information Center of the Chinese Academy of Agricultural Sciences, respectively. According to the ratio of the county data to the Inner Mongolia data of extant livestock year-end population, the sheep and cattle populations out of fold in Inner Mongolia were distributed to county data of livestock populations out of fold. The city horse-population data (from the *IMSY*) were averaged with county data. From the county data on the Inner Mongolia grasslands (Meng, 1993) and dynamic changes of Inner Mongolia grassland area (Zou et al., 2002), we calculated the grassland area of Inner Mongolia counties in 2006. Human population data were acquired from the *IMSY*. Coal and petroleum consumption data of Inner Mongolia, which were acquired from the *China Energy Statistical Yearbook* (National Bureau of Statistics, 1985, 1999), were distributed to county-level data according to the county human-population data. Sheep meat, cattle meat, and milk production data for Inner Mongolia were also from the *IMSY*. The livestock meat and milk data were distributed to county-level data according to the county livestock population data.

We compared the sum of each county's livestock data from the *IMSY* with the livestock data of Inner Mongolia from the *Rural Statistical Yearbook of China* (*RSYC*), and the differences between the two were within ±1%. The grassland area data were from surveys and from deductions of remote-sensing data (Zou et al., 2002). So the range of uncertainty in the data of livestock, grassland area, and livestock product was ±1%. The human population data of the *IMSY* and the *RSYC* were consistent. So we regard the county human population data from the *IMSY* as exact data.

Also, the energy-consumption data were regarded as exact data.

3.2 *Results on N budget in Inner Mongolia*

3.2.1 *N outputs from grassland in Inner Mongolia in* 2006

The N outputs from grassland in Inner Mongolia in 2006 simulated by the regional N cycle module for grassland in the IAP-N model were $1.2\times10^9\pm0.2\times10^9$ kg. Of these, N output by livestock intake accounted for 85%, or the equivalent of $1.0\times10^9 \pm 0.1 \times 10^9$ kg. The N output by gas emissions from the grassland and by leaching were $1.5\times10^8 \pm 0.8\times10^8$ kg and $2.2\times10^7 \pm 1.9\times10^7$ kg, respectively. Therefore, the most important pathway for N loss in grassland is livestock intake. N gaseous and leaching losses contributed to 13% and 2% of the N outputs, respectively. The NH_3 emission from grasslands in Inner Mongolia in 2006 simulated by the grassland module was 2.81 ± 1.44 kg hm^{-2}. Wang et al. (1997) assumed that the NH_3 emission from livestock and humans was 1.82 kg hm^{-2} yr^{-1}. The NH_3 emissions from the grassland module estimation were higher than the estimations by Wang et al. (1997). The quantitative contribution of NO and N_2O emissions to the nitrogen budget, while important for atmospheric chemistry and the greenhouse effect, are usually $<5\%$ of the total nitrogen import or export (Ammann et al., 2009). The N_2O emissions from grasslands in Inner Mongolia in 2006 were estimated to be 0.10 ± 0.09 kg N_2O–N hm^{-2}. The annual N_2O emissions from temperate grasslands simulated by the denitrification–decomposition (DNDC) model were 0.18 kg hm^{-2} (Xu-Ri et al., 2003) and 0.23 kg hm^{-2}, respectively (Zhang et al., 2010). Mosier et al. (1996) estimated that N_2O emissions from North America short-grass steppes were 0.14 kg hm^{-2}. Compared with these estimations, our simulation results were reasonable.

The spatial distribution of the N output by livestock intake is given in detail in Fig. 2a. The N output by livestock intake in the middle of Inner Mongolia was intensive, whereas, in the western and northeastern boundary counties, outputs were very small. The N output by livestock intake was related to livestock population. Consequently, in the middle of Inner Mongolia, in which both the sheep and cattle population were large (Figs. 3b and c), the N output by livestock intake was also large. Figure 2b shows the spatial distribution of the N output by gas emissions in Inner Mongolia grassland in 2006. Similar to the N output by livestock intake, the N output by gas emissions in the middle of Inner Mongolia was large, but western and northeastern Inner Mongolia also contributed N gas emissions. The highest N gas emission occurred in

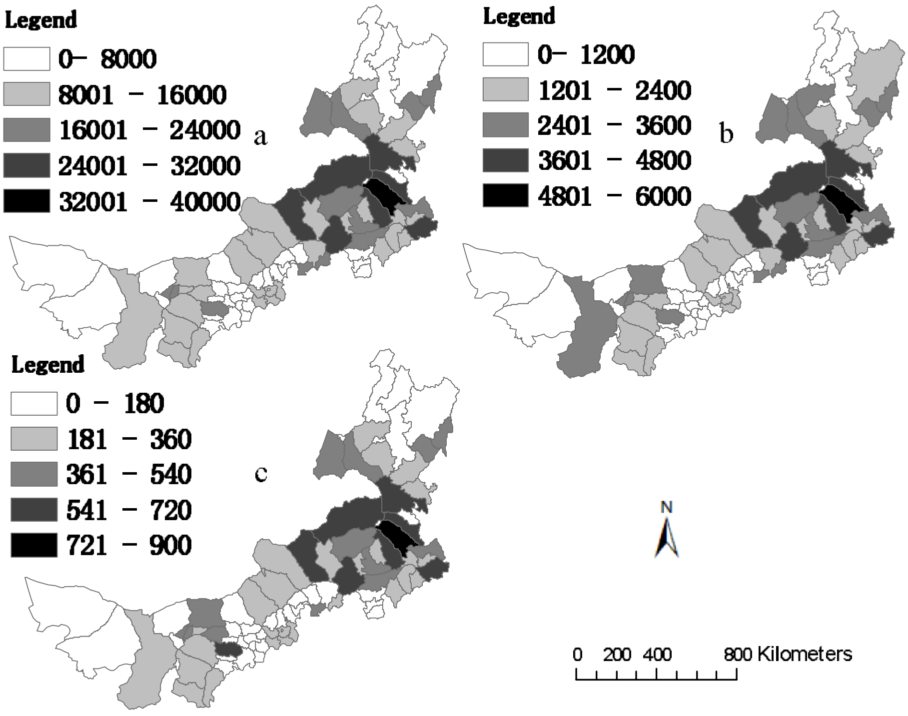

Fig. 2. Spatial distributions of the N outputs from grassland in Inner Mongolia in 2006: (a) N output by livestock intake; (b) N output by gas emissions from grassland; and (c) N output by leaching/runoff (units: 10^6 g).

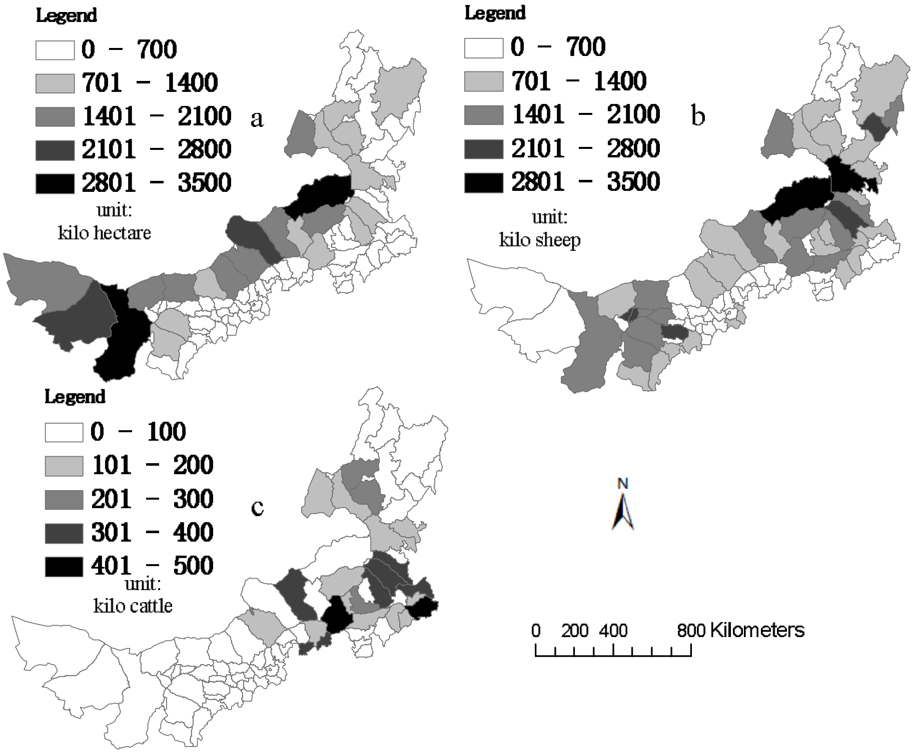

Fig. 3. Spatial distributions of grassland area and livestock population in Inner Mongolia in 2006: (a) area; (b) sheep population; and (c) cattle population.

Zhaluteqi. The N output by leaching was estimated according to N from livestock excreta; therefore, the spatial distribution of N output by leaching in Inner Mongolia grassland in 2006 (Fig. 2c) was related to livestock population (Figs. 3b and c).

3.2.2 *N inputs into grassland in Inner Mongolia in 2006*

The N input into the grassland of Inner Mongolia in 2006 was $1.0\times10^9 \pm 0.2 \times 10^9$ kg, with $1.3\times10^8 \pm 0.01\times10^8$ kg from biological fixation, $5.1\times10^8 \pm 1.1\times10^8$ kg from atmospheric deposition, and $3.6\times10^8 \pm 0.9 \times 10^8$ kg from livestock excreta, which accounted for 13%, 51%, and 36% of N inputs into the grassland, respectively. The N_2 biological fixation in Inner Mongolia grassland was 2.70 ± 0.02 kg hm^{-2}, using the grassland module for IAP-N. Fixed N_2 was between 40 kg N hm^{-2} and 60 kg N hm^{-2} in *Trifolium pretense* grasslands in Sweden (Huss-Danell et al., 2007). The total amount of N fixed in the mixture of *Lolium perenne* and *T. repens* in Denmark varied between 100 kg N hm^{-2} and 235 kg N hm^{-2} per year (Vinther and Jensen, 2000). Apparently biological N_2 fixation in Inner Mongolia grassland from this study is very small. The spatial distribution of N input by biological fixation in Inner Mongolia grassland in 2006 (Fig. 4a) was consistent with the distribution of grassland area (Fig. 3a). N input by biological fixation was large in western and northern Inner Mongolia, especially in Dong Ujimqin Qi and Alxa Zuoqi. The higher N input by atmospheric deposition occurred in middle and eastern Inner Mongolia (Fig. 4b). High N input by livestock excreta in Inner Mongolia grassland in 2006 was found in the middle of Inner Mongolia (Fig. 4c), where both the sheep and cattle populations were large (Figs. 3b and c).

3.2.3 *N budgets of grassland and the livestock/human pool*

The N budget of the grassland in Inner Mongolia in 2006 simulated by the grassland module for the IAP-N model was $-1.7\times10^8 \pm 0.6 \times 10^8$ kg. That is to say, the net N loss from Inner Mongolia grassland in 2006 was 3.41 ± 1.16 Kg hm^{-2}. Figure 5 shows the spatial distribution of the N budget for the grasslands of Inner Mongolia in 2006, with 57% of the provincial net N loss occurring in the 10 counties located in the middle of the region. Net N loss was most intensive in Jarud Qi and Horqin Youyi Zhongqi. Net N loss in many counties in the northern Inner Mongolia and in parts of the western Inner Mongolia occurred to a certain extent. In some western counties, no net N loss occurred in 2006. The N cycle caused by livestock plays a crucial role in the input and output of

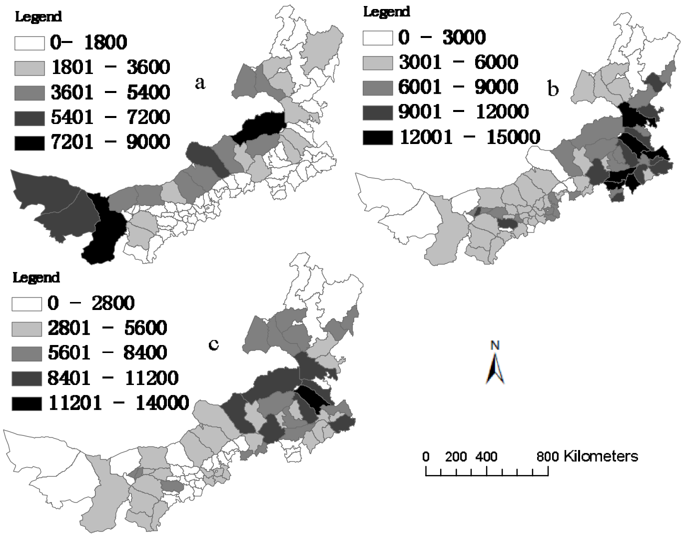

Fig. 4. Spatial distributions of the N inputs into grassland in Inner Mongolia in 2006: (a) N input by biological fixation; (b) N input by atmospheric deposition; and (c) N input by livestock excreta deposition (units: 10^6 g).

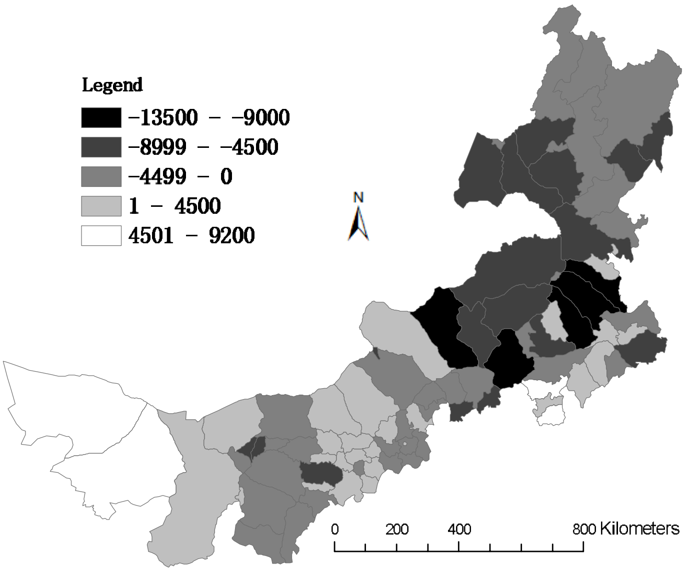

Fig. 5. Spatial distribution of the Nbudgets in the Inner Mongolia grassland ecosystem in 2006 (units: 10^6 g).

N from grassland. The region in which net N loss was the largest was the region where both the sheep and cattle population were large (Figs. 3b and c). The livestock/human N budget in Inner Mongolia in 2006 was $1.2\times10^8\pm1.1\times10^8$ kg. The absolute value of the N budget was close to that of the N budget of grassland; therefore, a majority of the N loss in the grassland contributed to the growth of the N income of the livestock/human pool. The N budget of Inner Mongolia grassland was negative for native grassland without N fertilization. Ammann et al. (2009) assessed the N budget of temperate grassland fields. The results showed that, in addition to large import and export contributions of fertilizer and harvest, the biological N_2 fixation, the emission of NH_3, and the emission of N_2 are highly relevant. In addition, the contribution of dry and wet depositions cannot be neglected. On the other hand, the quantitative contribution of NO and N_2O emission to the nitrogen budget are negligible for N budget consideration. The important components

APPENDIX A

Table A. Value range and references of the parameters.

Parameter	Value range	References
sheep_intake	384–522	Bai et al. (1998)
cattle_intake	2357–3204	Adapted from Bai et al. (1998), Wang et al. (2006), Huang (2000), Lu et al. (1996), and National Bureau of Statistics (1993)
horse_intake	1474–2004	Adapted from Bai et al. (1998), Wang et al. (2006), Huang (2000), and Lu et al. (1996)
N_grass	0.016	Chen and Wang (2000)
f_sheep	2.3–8.82	Adapted from Wang et al. (2006), Huang (2000), and Lu et al. (1996)
f_horse	22.3	Adapted from Wang et al. (2006)
f_cattle	35.66	Adapted from Wang et al. (2006) and National Bureau of Statistics (1993)
EF_N_2O	0.01–0.2 or −0.044–0.228	Adapted from Wolf et al. (2010) and Holst et al. (2007a); high value for typical grassland; low value for severe degraded grassland
r_grz	0.67	Wu (1990)
f_NH_3_grz	0.2–0.3	Li and Chen (1997)
EF_NO	0.01–0.04 or 0.006–0.026	Adapted from Holst et al. (2007b), Wolf et al. (2010) and Holst et al. (2007a); high value for typical grassland; low value for severe degraded/desertified grassland
EF_N_2	0.01–0.2 or −0.044–0.228	Adapted from Schlesinger (2009), Wolf et al. (2010), and Holst et al. (2007a); high value for typical grassland; low value for severe degraded/desertified grassland
r_fold	0.33	Wu (1990)
f_N_2O_fold	0.0037–0.0053	Adapted from Chen et al. (2010) and Liu (2007)
f_NH_3_fold	0.2–0.3	Li and Chen (1997)
f_NO_fold	0.00041–0.0018	Adapted from Liu et al. (2009) and Liu (2007)
f_N_2_fold	0.009–0.041	Adapted from Schlesinger (2009), Chen et al. (2010), and Liu (2007)
f_N_2O_burn	0.007	Zheng et al. (2008)
f_NH_3_burn	0.034	Zheng et al. (2008)
f_NO_x _burn	0.121	Zheng et al. (2008)
f_N_2_burn	0.467	Zheng et al. (2008)
f_human	5.4	Lu et al. (1996)
f1	0.85	Zheng et al. (2008)
f2	0.05	Surveyed
f21	0.001	Zheng et al. (2008)
f3	0.95	Surveyed
f31	0.005	Zheng et al. (2008)
f_N_2O	0.0048	Adapted from Zheng et al. (2008)
f_NH_3	0.2–0.3	Li and Chen (1997)
f_NO	0.0005–0.0016	Adapted from Zheng et al. (2008), Chen et al. (2010), Liu (2007), and Liu et al. (2009)
f_N_2	0.008–0.054	Adapted from Zheng et al. (2008), Chen et al. (2010), Schlesinger (2009), and Liu (2007)
f_leaching	0.01–0.06	Adapted by Zhu and Zhang (2010), Xing and Zhu (1997), Yi and Xue (1993), Yuan et al. (1995), Dai and Zhao (1992), Ma et al. (1997), Liu et al. (2004), and Haynes and Williams (1993)
f_fold_leaching	0.01–0.18	Adapted from Zhu and Zhang et al. (2010), Xing and Zhu (1997), Yi and Xue (1993), Yuan et al. (1995), Dai and Zhao (1992), and Ma et al. (1997)
f_bn	2.7	Cleveland et al. (1999)
f_deposition	0.819	Zheng et al. (2008)
f_N_2O_grz	0.001–0.002	Adapted from Wolf et al. (2010), Wang et al. (2006), Huang et al. (2000), and Lu et al. (1996)
f_NO_grz	0.0004–0.001	Adapted from Wolf et al. (2010), Wang et al. (2006), Huang et al. (2000), and Holst et al. (2007b)
f_N_2_grz	0.001–0.002	Adapted from Wolf et al. (2010), Wang et al. (2006), Huang et al. (2000), and Schlesinger (2009)
f_lightning	0.018–0.032	Adapted from Jaffe (2000) and Galloway et al. (2004)

Table A. (Continued)

Parameter	Value range	References
EF_C	2.82	Adapted from Zhang et al. (2007) and Ohara et al. (2007); Adapted from National Bureau of Statistics (1985 and 1999)
EF_P	3.45	Adapted from Zhang et al. (2007) and Ohara et al. (2007); Adapted from National Bureau of Statistics (1985, 1999)
human_cereal	196	National Bureau of Statistics (2007)
cereal_N	0.018	Common sense
meat_N	0.024	Common sense
milk_N	0.0048	Common sense
human_meat	5.57	National Bureau of Statistics (2007)
human_milk	3.15	National Bureau of Statistics (2007)

to the N budget of those results were also crucial in our simulation results except for N_2 emission due to arid conditions of Inner Mongolia.

4. Conclusion

A regional N cycle module was designed for the IAP-N model, which was originally developed to simulate N cycling in cropland regions. A case study showed that this newly developed module could simulate the N budget of the semiarid grassland in Inner Mongolia. As the model estimated, the most important pathway of N output from the Inner Mongolian grassland in 2006 was livestock intake, especially in middle Inner Mongolia. Biological fixation, atmospheric deposition, and livestock excreta deposition were comparably important for the N inputs into the Inner Mongolian grassland. The N cycles related to livestock played a crucial role in the N balance of grassland. Our model simulation yielded an N budget of $-1.7\times10^8\pm0.6\times10^8$ kg in 2006, which indicates an obvious net N loss. As compared with the very limited estimations by other authors, the results of our model simulation for the Inner Mongolian grassland showed good agreement. The case study for Inner Mongolia showed that the new module designed in this study captured the characteristics of the N balance situation in the grasslands of Inner Mongolia. So this module could adapt the IAP-N model to semiarid grassland area.

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REFERENCES

Ammann, C., C. Spirig, J. Leifeld, and A. Neftel, 2009: Assessment of the nitrogen and carbon budget of two managed temperate grassland fields. *Agriculture, Ecosystems and Environment*, **133**, 150–162.

Bai, Y. F., Z. X. Xu, G. Zhao, J. Yang, and Bao-xiang, 1998: Study on the grazing behavior of Mongolia sheep. *Journal of Inner Mongolia Institute of Agriculture and Animal Husbandry*, **19**(3), 31–37. (in Chinese with English abstract)

Beier, C., and Coauthors, 2009: Carbon and nitrogen balances for six shrublands across Europe. *Global Biogeochemical Cycles*, **23**, doi: 10.1029/2008GB003381.

Bolle, H. J., W. Seiler, and B. Bolin, 1986: Other greenhouse gases and aerosols. *The Greenhouse Effect, Climate Change, and Ecosystem*, Bolin et al., Eds., John Wiley & Sons, New York, 157–205.

Brown, L., S. Armstrong Brown, S. C. Jarvis, B. Syed, K. W. T. Goulding, V. R. Phillips, R. W. Sneath, and B. F. Pain, 2001: An inventory of nitrous oxide emissions from agriculture in the UK using the IPCC methodology: Emission estimate, uncertainty and sensitivity analysis. *Atmos. Environ.*, **35**, 1439–1449.

Chen, W. W., B. Wolf, N. Brüggemann, K. Butterbach-Bahl, and X. H. Zheng, 2010: Annual emission of greenhouse gases from sheepfolds in Inner Mongolia. *Plant Soil*, **340**, 291–301.

Chen, Z. Z., and S. P. Wang, 2000: *Typical Grassland Ecosystem of China*. China Science Press, Beijing, 229pp. (in Chinese)

Cleveland, C. C., and Coauthors, 1999: Global patterns of terrestrial biological nitrogen (N_2) fixation in natural ecosystems. *Global Biogeochemical Cycles*, **13**, 623–645.

Dai, T. S., and Z. S. Zhao, 1992: Case study on the chemical from conversion and leaching of nitrogen and phosphorous in the irrigated plain area of Haihe River Basin. *Acta Scientiae Circumstantiae*, **12**, 497–501. (in Chinese)

Freibauer, A., 2003: Regionalised inventory of biogenic greenhouse gas emissions from European agriculture. *European Journal of Agronomy*, **19**, 135–160.

Galloway, J. N., and Coauthors, 2004: Nitrogen cycles: Past, present, and future. *Biogeochemistry*, **70**, 153–226.

Haynes, R. J., and P. H. Williams, 1993: Nutrient cycling and soil fertility in the grazed pasture ecosystem. *Advances in Agronomy*, **49**, 119–199.

Heeb, N. V., A. M. Forss, S. Brühlmann, R. Lüscher, C. J. Saxer, and P. Hug, 2006: Three-way catalyst-induced formation of ammonia-velocity- and acceleration-dependent emission factors. *Atmos. Environ.,* **31**, 5986–5997.

Holst, J., C. Y. Liu, Z. S. Yao, N. Brüggemann, X. H. Zheng, X. G. Han, and K. Butterbach-Bahl, 2007a: Importance of point sources on regional nitrous oxide fluxes in semi-arid steppe of Inner Mongolia, China. *Plant Soil*, **296**, 209–226.

Holst, J., and Coauthors, 2007b: Microbial N turnover and N-Oxide ($N_2O/NO/NO_2$) fluxes in semi-arid grassland of Inner Mongolia. *Ecosystems*, **10**, 623–634.

Huang, Y. K., 2000: Use of enzyme to reduce environmental pollution caused by manure. *Agro-Environment and Development*, **17**(2), 39–41. (in Chinese with English abstract)

Huss-Danell, K., E. Chaia, and G. Carlsson, 2007: N_2 fixation and nitrogen allocation to above and below ground plant parts in red clover-grasslands. *Plant Soil*, **299**, 215–226.

IPCC, 2001: *The Scientific Basis. Contribution of Working Group I to the Third Assessment Report*, Cambridge University Press, Cambridge, United Kingdom and New York, USA, 786pp.

IPCC, 2007: *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report*, Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Jaffe, D. A., 2000: The nitrogen cycle. *Earth System Science: From Biogeochemical Cycles to Global Change*, Jacobson et al., Eds., Academic Press, Amsterdam, 322–342.

Li, X. Z., and Z. Z. Chen, 1997: Nitrogen loss and management in grazed grassland. *Climatic and Environmental Research*, **2**(3), 241–250. (in Chinese with English abstract)

Liu, C. Y., 2007: The study of biosphere-atmosphere exchange of CH_4, N_2O and NO_x in a semi-arid steppe in Inner Mongolia, China. Ph. D. dissertation, Institute of Atmospheric Physics, Chinese Academy of Sciences. 107pp. (in Chinese with English abstract)

Liu, C. Y., J. Holst, Z. S. Yao, N. Brüggemann, K. Butterbach-Bahl, S. H. Han, X. G. Han, and X. H. Zheng, 2009: Sheepfolds as "hotspots" of nitric oxide (NO) emission in an Inner Mongolian steppe. *Agriculture, Ecosystems and Environment*, **134**, 136–142.

Liu, Z. K., S. P. Wang, J. G. Han, Y. F. Wang, and Z. Z. Chen, 2004: Changes of soil chemical properties in sheep urine patches in Inner Mongolia steppe. *Chinese Journal of Applied Ecology*, **15**(12), 2255–2260. (in Chinese with English abstract)

Lu, R. K., H. X. Liu, D. Z. Wen, S. W. Qin, J. Y. Zheng, and Z. Q. Wang, 1996: Nutrient cycle and balance in Chinese typical agriculture ecosystems: 2. Factors of nutrient input in cropland. *Chinese Journal of Soil Science*, **27**(4), 151–154. (in Chinese)

Ma, L. S., Z. Q.Wang, S. M. Zhang, X. F. Shuiming, and G. Y. Zhang, 1997: Pollution from agricultural non-point sources and its control in river system of Taihu Lake, Jiangsu. *Acta Scientia Circumstantiae*, **17**, 39–47. (in Chinese)

Meng, Y. D, 1993: *Data on the Grassland Resources of China*. China Agricultural Science and Technology Press, Beijing, 366pp. (in Chinese)

Mosier, A. R., W. J. Parton, D. W. Valentine, D. S. Ojima, D. S. Schimel, and J. A. Delgado, 1996: CH_4 and N_2O fluxes in the Colorado shortgrass steppe: 1. Impact of landscape and nitrogen addition. *Glob Biogeochem Cycles*, **10**, 387–399.

National Bureau of Statistics, 1985: *China Energy Statistical Yearbook in 1985*. China Statistics Press. (in Chinese)

National Bureau of Statistics, 1999: *China Energy Statistical Yearbook in 1999*. China Statistics Press. (in Chinese)

National Bureau of Statistics, 1993: *Rural Statistical Yearbook of China, 1993*. China Statistical Press. (in Chinese)

National Bureau of Statistics, 2007: *Rural Statistical Yearbook of Chin, 1997*. China Statistical Press. (in Chinese)

Ohara, T., H. Akimoto, J. Kurokawa, N. Horii, K. Yamaji, X. Yan, and T. Hayasaka, 2007: An Asian emission inventory of anthropogenic emission sources for the period 1980–2020. *Atmos. Chem. Phys.*, **7**, 4419–4444.

Ryden, J. C., P. R. Ball, and E. A. Gardwood, 1984: Nitrate leaching in grassland. *Nature*, **311**, 50–541.

Schlesinger, W. H., 2009: On the fate of anthropogenic nitrogen. *PNAS*, **106**(1), 203–208.

Statistical Bureau of Inner Mongolia Autonomous Region, 2007: *Inner Mongolia Statistical Yearbook, 2007*. China Statistical Press. (in Chinese)

Vinther, F. P., and E. S. Jensen, 2000: Estimating legume N_2 fixation in grass-clover mixtures of a grazed organic cropping system using two ^{15}N methods. *Agriculture, Ecosystems and Environment*, **78**, 139–147.

Vitousek, P. M., S. Hattenschwiler, L. Olander, and S. Allison, 2002: Nitrogen and nature. *Ambio*, **31**, 97–101.

Wang, F. H., W. Q. Ma, Z. X. Dou, L. Ma, X. L. Liu, J. X. Xu, and F. S. Zhang, 2006: The estimation of the production amount of animal manure and its environmental effect in China. *China Environmental Science*, **26**(5), 614–617. (in Chinese with English abstract)

Wang, W. X., X. F. Lu, Y. B. Pang, D. G. Tang, and W. H. Zhang, 1997: Geographical distribution of NH_3 emission intensities in China. *Acta Scientia Ecircumstantiae*, **17**(1), 2–7. (in Chinese with English abstract)

Wolf, B., and Coauthors, 2010: Grazing-induced reduction of natural nitrous oxide release from continental steppe. *Nature*, **464**, doi: 10.1038/nature08931.

Wu, G. Z., 1990: Relationship of sheep daily excretion and weight and feed intake. *Pasturage and Veterinary of Gansu*, **1**, 10–11. (in Chinese)

Xing, G. X., and A. L. Zhu, 1997: Preliminary studied on N_2O emission fluxes from upland soils and paddy soils in China. *Nutrient Cycling in Agroecosystem*, **49**, 58–63.

Xu-Ri, M. Wang, and Y. Wang, 2003: Using a modified DNDC model to estimate N_2O fluxes from semi-arid grassland in China. *Soil Biology and Biochemistry*, **35**, 615–620.

Yi, X., and C. Z. Xue, 1993: Study on nitrogen fertilizer pollution by leaching in stratified old manured loessial. *Agro-environmental Protection*, **12**, 250–253. (in Chinese)

Yuan, F. M., Z. M. Chen, Z. H. Yao, C. H. Zhou, G. M. Fu, Y. L. Song, and X. P. Li, 1995: NO_3^--N transformation, accumulation and leaching loss in surface layer of Char-Soil in Beijing. *Acta Pedological Sinica*, **32**, 388–399. (in Chinese)

Zhang, F., J. Qi, F. M. Li, C. S. Li, and C. B. Li, 2010: Quantifying nitrous oxide emissions from Chinese grasslands with a process-based model. *Biogeosciences*, **7**, 1675–1706. (in Chinese with English abstract)

Zhang, Q., and Coauthors, 2007: NO_x emission trends for China, 1995–2004: The view from the ground and the view from space. *J. Geophys. Res.*, **112**, doi: 10.1029/2007JD008684.

Zhao, T. Q., Z. Y. Ouyang, L. Q. Jia, and H. Zheng, 2004: Ecosystem services and their valuation of China grassland. *Acta Ecologica Sinica*, **24**(6), 1101–1110. (in Chinese with English abstract)

Zheng, X. H., C. B. Fu, X. K. Xu, X. D. Yan, Y. Huang, S. H. Han, F. Hu, and G. X. Chen, 2002: The Asian nitrogen cycle case study. *Ambio*, **31**(2), 79–87.

Zheng, X. H., C. Y. Liu, and S. H. Han, 2008: Description and application of a model for simulating regional nitrogen cycling and calculating nitrogen flux. *Adv. Atmos. Sci.,* **25**(2), 181–201, doi: 10.1007/s00376-008-0181-7.

Zhu, Z. L., and F. S. Zhang, 2010: *Basic Studies on Nitrogen in Major Agriculture Ecosystems and Efficient Utilization of Nitrogen Fertilizers.* China Scientific Press, Beijing, 400pp. (in Chinese)

Zou, Y. R., X. L. Zhao, Z. X. Zhang, Q. B. Zhou, and W. B. Tan, 2002: An analysis of dynamic changes of China's grassland on the basis of RS and GIS. *Remote Sensing for Land and Resources*, **51**, 29–33. (in Chinese with English abstract)