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Detailed regional predictions of N_2O and NO emissions from a tropical highland rainforest

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Abstract

Tropical forest soils are a significant source for the greenhouse gas N_2O as well as for NO, a precursor of tropospheric ozone. However, current estimates are uncertain due to the limited number of field measurements. Furthermore, there is considerable spatial and temporal variability of N_2O and NO emissions due to the variation of environmental conditions such as soil properties, vegetation characteristics and meteorology. In this study we used a process-based model (ForestDNDC-tropica) to estimate N_2O and NO emissions from tropical highland forest (Nyungwe) soils in southwestern Rwanda. To extend the model inputs to regional scale, ForestDNDC-tropica was linked to an exceptionally large legacy soil dataset. There was agreement between N_2O and NO measurements and the model predictions though the ForestDNDC-tropica resulted in considerable lower emissions for few sites. Low similarity was specifically found for acidic soil with high clay content and reduced metals, indicating that chemo-denitrification processes on acidic soils might be under-represented in the current ForestDNDC-tropica model. The results showed that soil bulk density and pH are the most influential factors driving spatial variations in soil N_2O and NO emissions for tropical forest soils. The area investigated (1113 km^2) was estimated to emit ca. 439 ± 50 t N_2O-N yr^{-1} (2.8–5.5 kg N_2O-N ha^{-1} yr^{-1}) and 244 ± 16 t NO-N yr^{-1} (0.8–5.1 kg N ha^{-1} yr^{-1}). Consistent with less detailed studies, we confirm that tropical highland rainforest soils are a major source of atmospheric N_2O and NO.

1 Introduction

Soils are both a source and a sink of gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). All these gases are potent greenhouse gases (GHG). In particular, N_2O is 298 times as potent as CO_2 and ranks third after CO_2 and CH_4 as a global warming agent (Meehl et al., 2007). In addition, NO emitted from soils acts as

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a precursor of tropospheric ozone, which contributes to the greenhouse effect as well (Delmas et al., 1997).

The concentrations of the atmospheric GHGs have accelerated during the past century, indicating an urgent need for process-based understanding of the factors influencing the exchange of these gases between the soil and atmosphere at a range of scales, as a route to developing effective mitigation strategies. Natural sources of atmospheric N_2O and NO are significant in the respective global budgets and include oceans and tropical forest soils. The importance of tropical forests as sink and source of carbon GHGs is relatively well known, but N_2O and NO fluxes from tropical forest soils are far less well characterized. On its own, tropical forest soils are identified as a major natural source for atmospheric N_2O (Matson et al., 1990; Bouwman et al., 1993; Mosier et al., 1998; Breuer et al., 2000; Kiese et al., 2002, 2003; Butterbach-Bahl et al., 2004; Werner et al., 2007b) and are responsible for an approximately 1.3 ± 0.3 Tg nitrogen (N) yr^{-1} (Werner et al., 2007a). Similarly, based on the few existing data, NO from tropical forest soils represent a significant source with estimates ranging from 1.1 to 3.0 Tg N yr^{-1} within the global atmospheric budget (Davidson and Kingerlee, 1997; Gut et al., 2002; Butterbach-Bahl et al., 2004). Further simulation results, using an N isotope coupled mechanistic biogeochemical model, showed that total gaseous losses, including N_2, from tropical rain forest soils in Hawaii contributed for ~26–48 % of total N losses (Bai and Houlton, 2009).

Production of N_2O and NO in tropical forest soils is closely linked to the microbial processes of nitrification when ammonia is oxidized to nitrate in the presence of oxygen, and denitrification when nitrate used as an electron acceptor instead of oxygen, as well as chemical process of chemo-denitrification when nitrite react with metallic cations such as Fe (II) (e.g. Davidson et al., 2000; Serca et al., 1994; Butterbach-Bahl et al., 2004).

To characterize and scale N dynamics biogeochemical models, such as the DeNitrification-DeComposition based models PnET-DNDC (Li et al., 2000; Stange et al., 2000; Butterbach-Bahl et al., 2001), ForestDNDC-tropica (Werner at al., 2007a)

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and LandscapeDNDC (Haas et al., 2012), simulate soil climate, litter decomposition and plant growth, in order to determine soil C and N turnover and predict the soil-atmosphere exchange of GHGs. Irrespective of extensive research on microbial nitrification and denitrification and their contribution to N_2O and NO fluxes (e.g. Matson and Vitousek, 1990; Davidson et al., 2000; Butterbach-Bahl et al., 2004; Lisboa et al., 2011; Rowlings et al., 2011) the magnitude of gaseous nitrogen (N) emissions for global sources are still highly uncertain at all scales.

Amongst others a high spatio-temporal variability in environmental factors is a reason for the high uncertainty of current regional and global estimates of GHG emissions from soils, in general (Kesik et al., 2005; Werner at al., 2007a). Moreover, for most regions little information exists on the spatial heterogeneity and/or average values of physico-chemical soil properties, driving biogeochemical models. Currently, global estimations of N_2O emissions for tropical forest rely mostly on the International Soil Reference and Information Center (ISRIC-WISE, with focus on tropical and subtropical regions), which does not distinguish between agriculture and natural land cover.

The estimation of N_2O emission from tropical forest in such a global study is based on soil properties, like OC, which are predominantly collected for agriculture soils that can be an obvious source of bias. Furthermore, global studies do not explicitly differentiate highland from lowland tropical forests, which strongly affects climate and soil properties. Given the uncertainty associated with current estimations of N_2O and NO emissions from global tropical forests, which rely on relatively few soil inventories from tropical forests, no reliable spatial explicit predictions for N-trace gases are available for the tropical forests.

Given the importance of N-trace gases in the GHG balance of tropical forests there is an urgent need to quantify the impact of the regional distribution of soil properties and vegetation characteristics on the model estimates of these gases. To do so, emphasis should be put on using regionally available legacy soil data to predict spatial N-trace gas emissions.

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Legacy soil data is data collected during historical soil surveys e.g. for the purpose of soil mapping are generally collected without any statistical criteria. Such legacy soil data can, however, be valuable for biogeochemical models as it is the best and the only available data. This also links to the wider discussion about uncertainty in biogeochemical models (Werner et al., 2007a), which have recently highlighted the potential effort for improving spatial information on soil and vegetation data from tropical forests.

In this study we incorporate historical soil data to predict regional N_2O and NO emissions from the mountainous tropical rainforest in Nyungwe national park, Rwanda, using the ForestDNDC-tropica biogeochemical model (Werner et al., 2007a). Using these predictions we aim to answer key questions such as: (1) what is the N_2O and NO source strength of a mountainous tropical forest soil? (2) To what extend do these values differ from current estimates? (3) And how sensitive is the ForestDNDC-tropica model to changes in driving (historical) input variables.

2 Material and methods

2.1 Site description

Nyungwe forest in southwestern Rwanda (2°17′S – 2°49′S/29°03′E – 29°29′E, 1485–2950 m a.s.l., Fig. 1a) is one of the largest and best-preserved mountainous rainforests in Africa. The forest occupies an area of about 100 000 ha dividing the Nile and the Congo river catchments. Overall temperatures vary between 8 and 29 degrees and yearly rainfall ranges from 1308 to 2071 mm yr^{-1}, with the rainy season lasting from September until May. The forest contains various ecosystems ranging from dense forest, bamboo groves to marshes, and contains approximately 1105 plant species, as well as high biodiversity of fauna. (Graham et al., 1995; Masozera and Alavalapati, 2004; Plumptre et al., 2007) The vegetation is characterized by *Entandrophragma excelsum, Parinari excelsa, Prunus Africana and Octotea usambarensis* (Van Ranst et al., 1997).

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2.2 Model description

Model description DeNitrification-DeComposition (DNDC) models (Li et al., 1992) have been developed for simulating ecosystem C and N-cycling and associated emission of trace gases. In particular, the ForestDNDC-tropica model includes sub-models that simulate soil climate, litter decomposition, plant growth and biogeochemical processes contributing to trace gases emissions in order to determine soil C and N turnover and predict the soil-atmosphere exchange of GHG from tropical forest soil.

In the soil climate sub-model, daily climate data is used to calculate soil temperature, moisture and oxygen profiles. This is done by considering soil properties (texture), and plant and microbial turnover processes of C and N. Forest growth is calculated depending on temperature, water and nitrogen availability. Litter production, water and nitrogen demand of plants and root respiration is linked with the soil and the decomposition sub-model. N-trace gas production, consumption and emission are calculated within the sub-models nitrification and denitrification.

In general, these simulations are carried out by considering soil properties such as texture, OC and N content, mineral soil pH and bulk density (BD), vegetation parameters (aboveground biomass, wood mass, leaf mass and floor mass) and climate data (daily precipitation, minimum and maximum temperature). A detailed description of the above mentioned input parameters is given in subsequent sections. In the present study, no modifications of the model were performed and the model set-up remained unchanged as compared to the Werner et al. (2007a) study. A more detailed description for the ForestDNDC-tropica model is given in Werner et al. (2007a).

2.3 Model input data

2.3.1 Soil data

We used the soil profile database of Rwanda produced based on a national soil surveys (1981–1993). The soil database gives a full description of ~2000 soil profiles

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covering the Rwandan territory (Imerzoukene and Van Ranst, 2002; Verdoodt and Van Ranst, 2006a; Verdoodt and Van Ranst, 2006b). Topsoil (0–30 cm) data of sand, silt, clay, gravel, organic carbon (OC), total nitrogen (TN), mineral soil pH, and litter layer pH for our study area was extracted from the database. We selected 147 soil profiles located within the Nyungwe forest. Summary statistics for all selected soil properties are shown in Table 1. Missing values for TN (30 % of the selected profiles) were estimated by regression equation which was based on a statistical analysis of the complete datasets: TN = 0.0994 × OC 0.7178 ($R^2 = 0.74$, $p < 0.05$). Since soil bulk density values are largely missing in the original survey, bulk density was derived using specific pedo-transfer functions (PTF) for tropical highland forest soils (Gharahi Ghehi et al., 2012b).

2.3.2 Weather data

No long-term meteorological data from the forest were available and therefore daily weather data for the years 1981–1993 from the nearest three climatological weather stations at an altitude of ∼2000 m and an average distance to the forest of < 5 km were used (Minagri and CTB/BTS, 1993a, 1993b). In addition to past thirteen years climate data, we used more recent years (2007–2008) data measured at the Uwinka climate station (2°28′43.3″S, 29°12′00″E, 2465 m a.s.l.) located within the Nyungwe forest which has been established on 2007. The climatological data used, consisted of daily precipitation and daily minimum and maximum temperatures.

Daily weather data were spatially interpolated for the forest using the Thiessen polygon approach in GIS (geographic information system) (ESRI ArcMap 9.3 software). The mean annual temperature and precipitation (1981–1993) for the climate polygons were 16.8 °C and 1458 mm, respectively. For the northern region of the Nyungwe forest, decreased amounts in annual precipitation and higher values of mean annual temperature have been observed. The average annual mean temperature and precipitation (2007–2008) at Uwinka climate station is 14.5 °C and 1824.7 mm, respectively. The rainfall during the recent years was slightly higher than the average rainfall observed

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in most of the years during the period 1981–1993. In the rainy seasons of the years 2007–2008, monthly rainfall was approximately more than 150 mm and higher than during the years 1981–1993 (Fig. 2).

2.3.3 Vegetation data

We used the Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS, Smith et al., 2001) to derive a regional distribution of aboveground biomass estimates for Nyungwe forest. The LPJ-GUESS is an object-oriented, modular framework for modeling the dynamics of ecosystem structure and functioning at scales from plot to global scales, and at varying levels of process detail. The LPJ-GUESS model simulates vegetation dynamics and structure based on the tropical evergreen plant function type (PFT), which represent individual physiological, morphological and bioclimatic (Smith et al., 2001; Sitch et al., 2003). Taking time series of climate data (as mentioned above) and, given constraints of latitude, topography, and Nyungwe soil characteristics (as mentioned above), as input, the LPJ-GUESS model dynamically computed spatially explicit transient vegetation composition in terms of plant functional types, and their associated carbon and water budgets. Aboveground biomass (wood, leaf and floor mass) was extracted from the output of the LPJ-GUESS model and used as input drivers for ForestDNDC-tropica. The fine root mass was estimated as 0.7 × leaf mass (Kiese et al., 2005; Werner et al., 2007a). The spatial distribution of the simulated aboveground biomass is shown in Fig. 1b. The simulated aboveground biomass for the Nyungwe forest (ranging from 74 to 400 t C ha^{-1}) were in similar magnitude to those reported by Werner et al. (2007a) (100–225 t C ha^{-1} for tropical rainforest soils for eastern Africa). Furthermore, our simulated aboveground biomass up to 400 t C ha^{-1} were of similar magnitude as the reported aboveground biomass of ∼500 t C ha^{-1} for the northern part of the Nyungwe forest (Nsabimana, 2009).

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2.4 Model runs

In order to predict N_2O and NO emission from Nyungwe forest, soil, climate and vegetation data were integrated into a GIS database covering Nyungwe forest, with a spatial resolution of $0.025^\circ \times 0.025^\circ$. Many tropical forests are faced with a lack of soil data, thus requiring the generation of parameter maps based on rather limited datasets. The Inverse Distance Weighting (IDW) technique (Myers, 1993), a weighted average interpolator, was used for preparing the spatial distribution of model input parameters for grid cells where no observational data were available. We used a conservative linear weights function of 1 to interpolate the values. An IDW approach was preferred over kriging techniques because little spatial auto-correlation was observed for the selected properties. An example of the spatial distribution of the aboveground biomass and selected soil characteristics is shown in Fig. 1. Since many existing soil datasets for natural forested ecosystems comprise generally less than 30 % of the size compared to our dataset (ISRIC-WISE global soil profile data set; Nsabimana et al., 2008; Kiese et al., 2008; Werner at al., 2007a), we are argue that the spatial map of model input parameters (Fig. 1) is the best possible estimate of the spatial patterns of the topsoil property in tropical forested ecosystems at such a scale today.

All input data was formatted in ForestDNDC-tropica compatible formats. Finally, ForestDNDC-tropica was run in a daily time-step for the years 1981–1993 and 2007–2008 on this final vegetation and soil dataset. The model was run for a two years simulation period, using the first year as spin-up period in order to allow model internal C and N pools to equilibrate. The estimated N_2O emissions are converted to CO_2 equivalents for comparison with other GHG emissions. We used N_2O 100-yr global warming potential (GWP = 310).

2.5 Model validation with measured N-trace gases fluxes

To validate the ForestDNDC-tropica model output, N_2O and NO emission data for soils of the Nyungwe tropical forest by Gharahi Ghehi et al. (2012a) were used. The latter

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study carried out a medium-term incubation experiment with soils from 31 locations within the Nyungwe forest. Since the incubation data covered three water filled pore space levels (50, 70 and 90 % WFPS), a weighted mean WFPS average was used here for comparing soil incubation results and model simulations. On the basis of the laboratory simulated WFPS we calculated a weighted mean average of N_2O and NO emissions for each individual location (percent time at 40–60 %, 60–80 % and 80–100 % WFPS) using simulated WFPS values by ForestDNDC-tropica to extrapolate the incubation data. The extrapolated incubation N_2O and NO data were calculated using the following formula:

$$EI = \frac{[(x_{meas})_{50\%WFPS} \times \sum day_{mod40-60\%WFPS}] + [(x_{meas})_{70\%WFPS} \times \sum day_{mod60-80\%WFPS}] + [(x_{meas})_{70\%WFPS} \times \sum day_{mod80-100\%WFPS}]}{\sum day_{mod40-100WFPS}} \quad (1)$$

where EI is extrapolated incubation N_2O or NO data, x_{meas} is the laboratory measured N_2O or NO value, $\sum day_{mod}$ is sum of day of year of simulated WFPS values at 40–60 %, 60–80 % and 80–100 % by ForestDNDC-tropica.

To further evaluate the model, the Friend beta sensitivity index (β) (Friend et al., 1993) was computed to assess the influence of individual model parameters on model output on a regional scale (e.g., Butterbach-Bahl et al., 2004). Different model parameters were varied one-at-a-time over their plausible range while keeping the others at their nominal value. We used the climate data of the year 1993 and calculated variation of simulated average N_2O emissions in response to changes in plus-minus 1 for pH, and plus-minus 25 % for BD and in plus-minus 50 % for other input parameters.

Sensitivity index is than defined as:

$$\beta = \frac{\frac{[N_2O]_1 - [N_2O]_0}{[N_2O]_0}}{\frac{P_1 - P_0}{P_0}} \quad (2)$$

where P_1 and P_0 are the individual input parameter that increased and decreased, respectively; and the β index is calculated from the resulting change in N_2O emissions

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($P_0 \rightarrow [N_2O]_0$ or $P_1 \rightarrow [N_2O]_1$). The deviation of the β value from zero would imply a proportional to the sensitivity of a given parameter and the sign of β indicates the direction of correlation (a negative or positive correlation) (Kiese et al., 2005; Werner et al., 2007a). We reported the average β values for all 147 data locations in the historical data set.

2.6 Change in historical soil data

The soil properties have been obtained at least three decades ago and may have changed in time due to logging activities; so changes of historical soil data over time can affect the overall uncertainty of GHG inventories. The possibility of changes of historical soil data over time was shown by selecting 29 locations out of the 147 sites in the Nyungwe forest, for which a soil sampling was performed by Gharahi Ghehi et al. (2012a) during September 2009. We carried out a comparative analysis of simulated values N_2O and NO using current with past input soil properties to test whether changes of historical soil data would significantly affect model outcome.

3 Result

3.1 Modeled N_2O and NO emissions

The simulated N_2O emission for Nyungwe forest for the period 1981–1993 range from 2.8 to 5.5 kg N ha^{-1} yr^{-1}, with an average of 3.8 ± 0.52 kg N ha^{-1} yr^{-1}. The emission rates for the period 2007–2008 vary between 2.2 and 4.7 kg N_2O-N ha^{-1} yr^{-1}, with an average value of 3.7 ± 0.40 kg N_2O-N ha^{-1} yr^{-1}. The highest N_2O emissions (4–5.5 kg N ha^{-1} yr^{-1}) are simulated in regions with a relatively high clay (> 30 %) or OC (> 4 %) content, namely north – northeast and south of the Nyungwe forest (Fig. 3). Lower emissions are estimated for the eastern part of the forest, an area with predominantly sandy soils. Total emissions from the entire Nyungwe forest are estimated

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at 373–504 t N_2O-N yr^{-1} (mean = 439 ± 50 t NO-N yr^{-1}) for the period 1981–1993 and 384 t N_2O-N yr^{-1} and 489 t N_2O-N yr^{-1} for 2007 and 2008, respectively (Fig. 4).

The magnitude of simulated NO emission ranges from 0.8 to 5.1 kg N ha^{-1} yr^{-1} for 1981–1993 periods, with an average of 2.0 ± 0.87 kg N ha^{-1} yr^{-1}. The emission rates for the period 2007–2008 range from 2.5 to 5.0 kg NO-N ha^{-1} yr^{-1}, with an average value of 3.8 ± 0.42 kg NO-N ha^{-1} yr^{-1}. Significantly lower NO emissions (0.8–2.0 ha^{-1} yr^{-1}) are seen in the center and towards the south of the forest, regions with high soil pH (pH > 4) or a relatively high OC (> 4 %) content (Fig. 3). The simulated total NO emission for 1981–1993 ranged from 207 to 255 t NO-N yr^{-1} (mean = 244 ± 16 t NO-N yr^{-1}) and 489 t NO-N yr^{-1} and 384 t NO-N yr^{-1} for 2007 and 2008, respectively (Fig. 4). The total soil NO emission in the year 1981–1993 was lower than in 2007–2008. These figures demonstrate that large discrepancy in climate data resulted in as much a two-fold increase in NO emission over recent years. However, model predictions that soil NO emissions are higher in wetter (2007–2008) as compared to dryer years (1981–1993) are in contrast to laboratory findings, were NO emissions decreased with increasing soil moisture.

3.2 Model validation with measured N-trace gases fluxes

For the 31 sites simulated mean N_2O and NO emissions were generally < 15 g N_2O-N ha^{-1} d^{-1}. Although most of the laboratory N_2O and NO agreed well with simulated data, a few sites showed measurements that were three to four times higher (Fig. 5).

The high measured N_2O and NO emission values of > 15 g N ha^{-1} d^{-1} (Fig. 5) in laboratory study of Gharahi Ghehi et al. (2012a) were somewhat surprising. They pointed out that chemo-denitrification might be an important production pathway due to high free iron concentration in these acidic soils.

Overall, the simulated N_2O and NO data showed an underestimation of the emission by ForestDNDC-tropica. Correlation analysis between measured and simulated N_2O

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and NO fluxes yielded non-significant correlations of $r = 0.24$, $p > 0.05$ and $r = 0.16$, $p > 0.05$, respectively.

However, when excluding high emission values (emissions $> 15\,g\,N_2O\text{-}N\,ha^{-1}\,d^{-1}$) from the laboratory data sets, we observed a significant correlation between measured and simulated values of N_2O ($r = 0.42$, $p < 0.05$) and NO ($r = 0.51$, $p < 0.05$) fluxes (Fig. 5).

Figure 6 illustrates the parameters included in the sensitivity analysis by varying the individual parameters by ±1 for pH, ±25 % for BD and ±50 % for other input parameters. This simple model sensitivity test was previously used in several modeling studies, for example Butterbach-Bahl et al. (2004), Kiese et al. (2005), and Werner et al. (2007a). Overall, soil BD and pH were the most sensitive parameters for both N_2O and NO emissions. The observed sensitivity of N_2O emission rates for the Nyungwe forest was comparable to other published N_2O simulation data for tropical rain forest ecosystems using the same model. Kiese et al. (2005) and Werner et al. (2007a) reported a pronounced sensitivity of N_2O emission rate to changes in pH and BD in tropical forest ecosystems in Australia and global tropical forests, respectively. The sensitivity of N_2O and NO emissions on leaf mass, temperature, rainfall, OC and clay content variability were lower as compared to changes in soil pH and BD.

Overall, the calculated β-values in this study were lower as compared to those in the Kiese et al. (2005) and Werner et al. (2007a), e.g. a β-value of 2.5 for pH in Werner et al. (2007a) compared to 0.67 in our study. These lower β-values probably come from the smaller range of possibly values due to the restricted simulation region. For example Werner et al. (2007a) selected 1000 simulated grid cells out of a global dataset to assess model sensitivity, whereas we determined the sensitivity of modeled N_2O and NO emissions on variations in input parameters by selecting all 147 locations sites in the Nyungwe forest.

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3.3 Change in historical soil data

The soil properties have been obtained at least three decades ago and may have changed in time due to logging activities; so changes of historical soil data over time can affect the overall uncertainty of GHG inventories. The possibility of changes of historical soil data over time was shown by selecting 29 locations out of the 147 sites in the Nyungwe forest, for which a soil sampling was performed by Gharahi Ghehi et al. (2012a) during September 2009. We carried out a comparative analysis of simulated values N_2O and NO using current with past input soil properties to test whether changes of historical soil data would significantly affect model outcome.

4 Discussion

4.1 N_2O and NO emissions

To the best of our knowledge, simulated and N_2O and NO emission from the Nyungwe forest represents the first explicit regional N_2O and NO emission inventory for a tropical forest on the African continent. The estimated annual average N_2O emission from Nyungwe forest ($\sim 3.8\,kg\,N\,ha^{-1}\,yr^{-1}$) is in line with simulated annual N_2O emissions from tropical rainforest soils for eastern Africa ($\sim 3.5\,kg\,N\,ha^{-1}\,yr^{-1}$) by Werner et al. (2007a).

On average the entire Nyungwe forest emits 439 t of N_2O-N and 244 t of NO-N per year (1981–1993) and $\sim$384–489 t N_2O -N and $\sim$489–384 t NO-N for period 2007–2008. Werner et al. (2007a) estimated the N_2O source strength of tropical forest soils of Africa (assuming a total rainforest area of $3.055 \times 10^6\,km^2$) to be $344\,000\,t\,N_2O\,yr^{-1}$, which is equivalent to 113 t for our area. The latter number is significantly lower than our mean estimate of $439\,t\,N_2O\text{-}N\,yr^{-1}$ (1981–1993). This discrepancy may be due to two principal factors. First, Werner et al. (2007a) used the soil profile data from the ISRIC-WISE soil database and linked these to the global FAO soil map, whereas we used 147

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soil data inside the tropical forest (Rwanda database). Specifically with regard to soil OC contents our database comes up with higher values as compared to the Werner et al. (2007a) study, as in the latter study soil OC contents of the most prominent soil classes in Africa was 1.38 % (our database: average of 5.5 %). Second, there are also differences in simulated years and origins of climate data.

The average model estimates in our study for N_2O (3.8 kg N ha^{-1} yr^{-1}) and NO (2.0 kg N ha^{-1} yr^{-1}) for the Nyungwe forest are also supported by field measurements from other studies. On average, the mean annual N_2O emission from tropical forest in Australia and southwest China was 1–3 kg N ha^{-1} yr^{-1} (Kiese et al., 2005; Werner et al., 2007a). Higher N_2O emissions (2.6 kg N ha^{-1} yr^{-1}) for forests in Kenya were reported by Werner et al. (2007b). In general, measurement of N_2O fluxes from tropical mountain forests range between 0.01 and 3.75 kg N ha^{-1} yr^{-1} (Breuer et al., 2000; Ishizuka et al., 2005; Holtgrieve et al., 2006; Purbopuspito et al., 2006; Köhler et al., 2009) and between 0.03 and 0.4 kg ha^{-1} yr^{-1} for NO (based on only one study of Davidson and Kingerlee, 1997). However, NO emissions up to 3 kg ha^{-1} (for a period of 3 months and not for one year) were reported for rain forests in Queensland, Australia at the onset of the rainy season (Butterbach-Bahl et al., 2004). Compared to other published NO emission data for other tropical rain forest ecosystems, the simulated NO emissions of up to 5 kg ha^{-1} yr^{-1} at the Nyungwe forest were high. This can be the effect of low soil pH values as ForestDNDC-tropica considers a chemo-denitrification algorithm for pH values lower than 4 as co-process of NO production only (pH < 4 cover ~ 92 % of the total forest area).

4.2 Model and model parameter uncertainty

Werner et al. (2007a) and Butterbach-Bahl et al. (2004) pointed out that spatial variations in regional N_2O and NO emissions were mainly resulting from differences in the spatial distribution of soil and climate characteristics. For example, the two-fold increase of total annual NO emission for 2007–2008 years (384–489 t NO-N yr^{-1})

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compared to 1981–1993 years (244 ± 16 t NO-N yr^{-1}) indicates that large discrepancy in climate data play a major role in the N dynamics.

The different rainfall pattern between 1981–1993 and 2007–2008 periods within the study area might be related to shifts in weather patterns due to adjacent land use/land cover change (LULCC) as an important climate forcing (Mahmood et al., 2010) or altitude difference of almost 500 m between the old stations and the Uwinka station which explains at least the differences in temperature. There is also a known but not well-documented gradual decrease in rainfall from west to east, and since two of the old stations are located east of the forest they are likely underestimating the precipitation in the forest.

The high NO emissions simulated during wetter years could be a consequence of the rapid mineralization of litter accumulated during the dry period. Specifically at the onset of the rainy season (six months) the effect of the rainfall events on surface litter decomposition is direct and more pronounced as compared to decomposition dynamics of root litter and organic matter in the mineral soil. Our high NO emissions simulated during wetter years most likely are the result of higher NO production in the surface litter layer. Though NO production was also simulated in these years in the mineral soil, this contributed only little to total emissions, since NO consumption in the mineral layer was increasing at the time. We emphasize that the simulated responses of high NO emissions to the rainfall events are in agreement with observation by Butterbach-Bahl et al. (2004). They observed that wetting events at the onset of the rainy season resulted in peak NO emissions cumulating to several kg of NO-N within a few weeks.

For our N_2O emissions such a clear effect between wetter and dryer years is not visible, since N_2O production in the model occurs mainly in the mineral layer. Again, increased soil moisture will increase anaerobiosis and simulate further conversion of N_2O to N_2, so that total emissions are less affected.

The variation in simulated N_2O and NO emissions in the Nyungwe forest also reflected the texture and soil physico-chemical properties. For instance, N_2O emissions exceeding 4 kg ha^{-1} yr^{-1} were found in the northwestern part of the forest, which

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is characterized by high clay and OC contents and low pH (< 4). Several authors (Nömmik, 1956, Weier and Gillam, 1986; Granli and Bockman, 1994) have shown that low pH decreases the activity of the N_2O-reductase, thereby increasing production of N_2O, rather than N_2 from denitrification. For nitrification, it has also been demonstrated that low pH < or = 4 values favor N_2O production (Sitaula and Bakken, 1993; Martikainen and De Boer, 1993; Kesik et al., 2006). All this is in agreement with field observations of N_2O emissions for different tropical lowland forest sites in Australia by Kiese and Butterbach-Bahl (2002) which revealed that low pH was a crucial factor driving high N_2O emissions.

The high NO emissions were found in the center and towards the north and north-eastern of the forest, which are growing on soil characterized by low soil pH and relatively high OC or high clay contents. Moreover, all in the study of Serca et al. (1994) the combined influence of low pH and high OC was used to estimate the NO production potential of forest soils in the Mayombe forest.

Furthermore, Gharahi Ghehi et al. (2012a) suggest that high N_2O and NO emissions for some sites in the Nyungwe forest are possibly due to chemo-denitrification processes. Chemo-denitrification is thought to occur when nitrite (NO_2^-) in acid soils reacts with organic components to produce NO and N_2O (Bremner, 1997). Under acidic conditions chemo-denitrification may be a significant source of NO, N_2O, N_2 when NO_2^- is reduced to NO, N_2O or N_2 with Fe (II) as an electron donor (Van Cleemput and Baert, 1984; Cooper et al., 2003).

We have evidence of chemical pathways for NO and N_2O production in the Nyungwe forest soils (see Supplement for detailed description). Our laboratory experiment argues that abiotic denitrification can be an important source of N_2O and NO under certain circumstances, i.e. low pH and present of reduced inorganic compounds (e.g. Fe (II)).

In the present version of ForestDNDC-tropica NO and N_2O is mainly simulated via microbial nitrification and dentrification pathways. Although chemo-denitrification has been included in ForestDNDC-tropica (soil pH < 4) our study suggests that rates of

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chemo-denitrification for NO production in tropical soils may still be underestimated and that it is likely to be necessary to introduce such a mechanism for N_2O as well.

In addition to pH, bulk density has a significant influence on N_2O and NO emissions. Increasing bulk density increases the anaerobic zone and increasing the probability for saturated moisture conditions following rainfall. This triggers denitrification and N_2O emissions and decreases NO emissions (Stange et al., 2000; Kiese et al., 2005). Therefore, in order to further improve N_2O and NO emissions from tropical forest, improved spatial maps of soil pH and bulk density are needed. In general, soil BD measurements have rarely been made in soil surveys. However, it has been shown that organic content can be used as a sole predictor of topsoil BD in tropical forest soils (Gharahi Ghehi et al., 2012b).

4.3 N_2O and NO emissions: an integrated approach

Although uncertainties remain in our model results we are confident that, given the available driving data, these results give us a good insight into the spatial and temporal variability in N_2O and NO emissions. A comparative analysis of current with past TN, pH, clay and OC content values for a select subset of 29 locations (see Gharahi Ghehi et al., 2012a) displayed significant differences for all soil driving information but the clay values ($p > 0.05$). This data shows that soil properties have changed over the last three decades.

The probable reasons for these changes in the Nuyngwe forest based on personal communication (G. Wallin, August 2012) and several field observations (P. Boeckx, 2005–2012) could be the following: (i) forest fires in eastern part of the forest in 1999, (ii) traditionally more disturbances occurs in the eastern part, although locally some mining and logging activities have been done in the west as well and (iii) disturbance caused by people normally have occurred where the forest have been accessible, thus in the same areas where the most extensive soil sampling has been carried out.

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We acknowledge that these changes could affect our estimates of N_2O and NO. However, soil structural properties free of anthropogenic disturbance are in general more stable and change little over time.

On a regional to global scale, N_2O emission from e.g. grassland in West/East Africa regions is estimated to be 15.0 Mt CO_2 equivalents (Stehfest and Bouwman, 2006). Considering our small study area (1113 km^2) our estimate with a range of 0.19–0.25 Mt CO_2 equivalents (373–505 t N_2O-N = 0.19-0.25 Mt CO_2) for 1981–2008 confirms the potential importance of tropical forests as a major source of atmospheric N_2O on a regional, national and even global scale.

5 Conclusions

Although, there is still a considerable uncertainty associated with our emission estimates, our results are providing a first spatial explicit predictions of N_2O and NO for tropical forest at this scale. The results are in line with other studies, confirming substantial N_2O and NO emissions from tropical forests, thereby suggesting that N_2O and NO losses play a major role in the N cycle of tropical forests. Though there are still several limitations (e.g. clustering of legacy data; chemo-denitrification only considered for NO but not for N_2O) our results show that state of the art process-based models in combination with site-specific (historical) input data can be used to improve tropical N_2O and NO emission estimates.

Temporal variability has shown to be sensitive to known processes such as changes in precipitation. Our study further corroborates the notion that soil BD content and pH are the most influential factors driving spatial variations in soil NO and N_2O emissions for tropical forest soils and should therefore receive priority is monitoring campaigns.

However, some abiotic processes that contribute to, but no completely integrate, into our N trace gas modelling effort were found. In particular, chemo-denitrification processes on acidic soils seem to be under represented in the current ForestDNDC-tropica model.

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Scaling N_2O values from the Nyungwe forest in CO_2 equivalents and comparing them to CO_2 emission equivalents from grassland in West/East Africa indicates that the GHG contribution of N_2O (and NO) emissions from tropical highland rainforest cannot be understated.

Supplementary material related to this article is available online at: http://www.biogeosciences-discuss.net/10/1483/2013/bgd-10-1483-2013-supplement.pdf.

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Table 1. Summary statistics for topsoil (0–30 cm) clay, silt, sand, gravel, organic carbon (OC), total nitrogen (TN), pH-soil, bulk density (BD) and pH-litter: mean, minimum (min), median, 25 and 75 percentile, maximum (max.), standard deviation (SD) and coefficient of variation (CV).

Parameter	n	Mean	Min	25 per.	Median	75 per.	Max.	SD	CV
Mineral topsoil									
Clay (%)	144	34	2.0	23.0	36.0	44.0	71.0	14.2	0.4
Sand (%)	144	43	9.0	32.0	40.0	53.0	86.0	17.2	0.4
Silt (%)	144	23	5.0	15.0	20.0	28.0	61.0	12.2	0.5
Gravel (vol.%)	144	1.8	0.0	0.0	0.0	0.0	47.0	6.1	3.4
OC (%)	147	5.5	0.3	3.6	5.3	7.0	15.1	2.5	0.5
TN (%)	101	0.3	0.1	0.2	0.3	0.4	0.6	0.1	0.3
pH-soil (–)	147	3.8	3.0	3.5	3.7	4.0	5.4	0.4	0.1
BD ($g\,cm^{-3}$)	147	0.92	0.80	0.94	0.94	1.02	1.28	0.13	0.14
Litter layer									
pH-litter (–)	129	4.1	3.0	3.6	3.9	4.4	7.5	0.8	0.2

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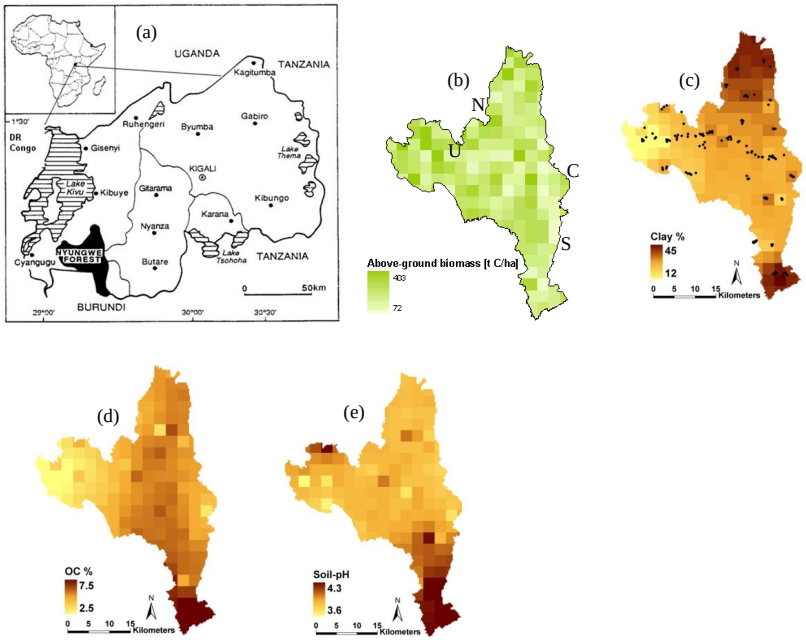

Fig. 1. Location of the Nyungwe forest in southwestern Rwanda **(a)**, spatial distribution of some selected model input parameters; above-ground biomass **(b)**, soil clay content and location of 147 legacy soil profiles (black bullets) **(c)**, soil organic carbon (OC) **(d)** and soil pH **(e)**. Location of three climate stations around the forest are shown by letter (N = north, C = Center, S = south); the recent climate station in the Nyungwe forest is shown by a U **(b)**.

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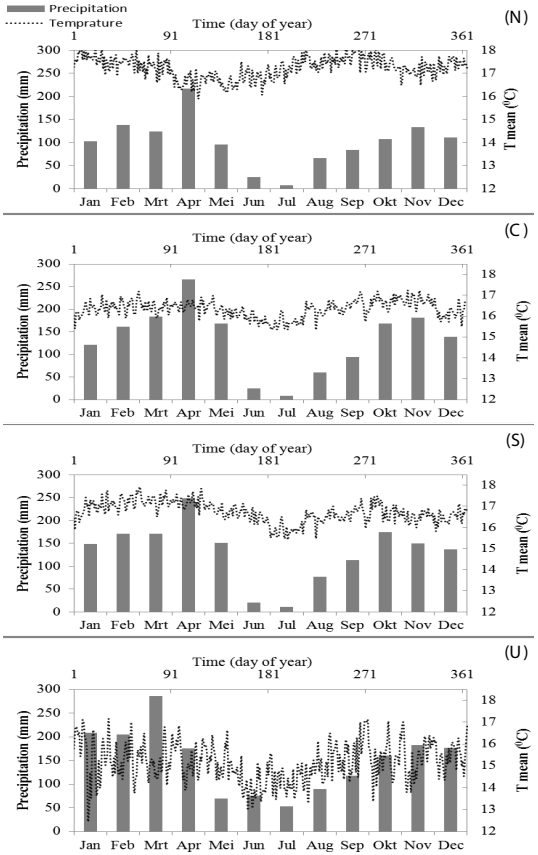

Fig. 2. Seasonal variation of climate parameters expressed as daily means (Temprature) and mounly means (Precipitation) from the three climate stations (from 1981 to 1993) north (N), Center (C), south (S), and the recent (2007 to 2008) climate data at Uwinka (U) in the Nyungwe forest increasing soil moisture.

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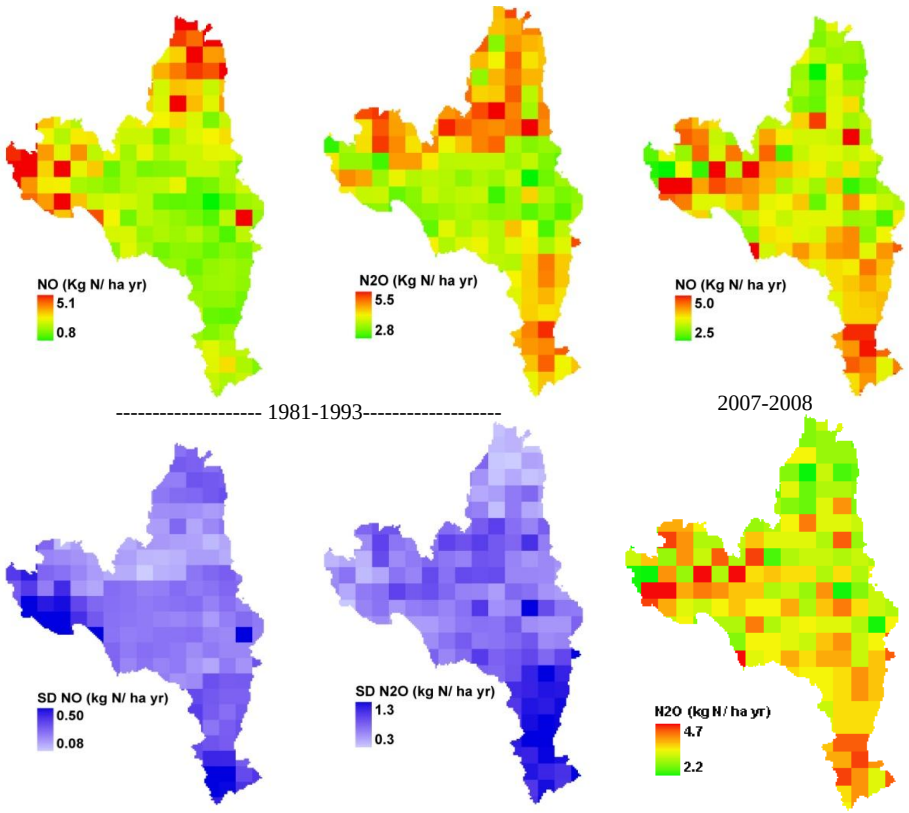

Fig. 3. Average annual (1981–1993; 2007 and 2008) predicted NO and N_2O emissions from the Nyungwe forest soil; and standard deviation (SD) indicating inter-annual variability of NO and N_2O fluxes.

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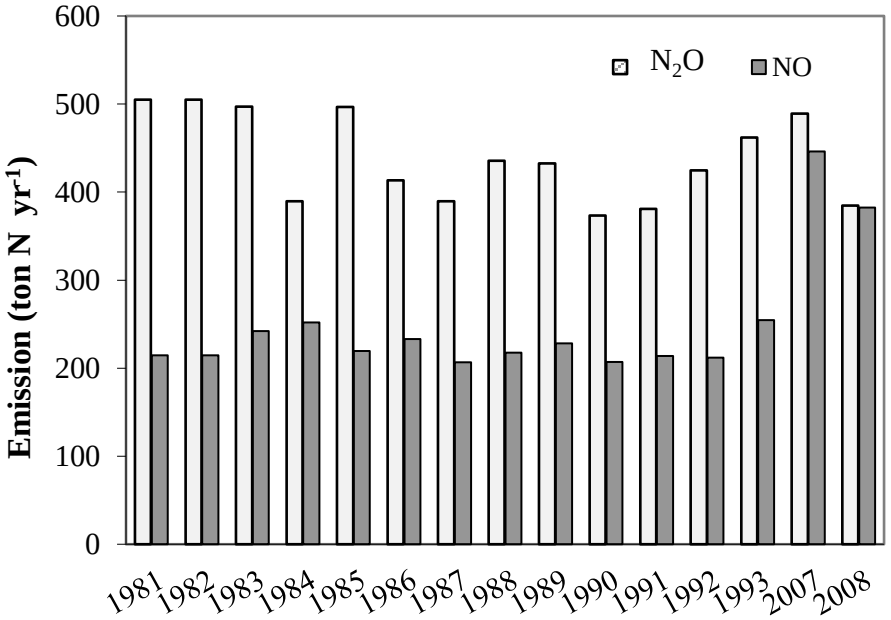

Fig. 4. Annual variation of total predicted N_2O and NO emissions from the Nyungwe forest soils for the years 1981–1993, 2007–2008.

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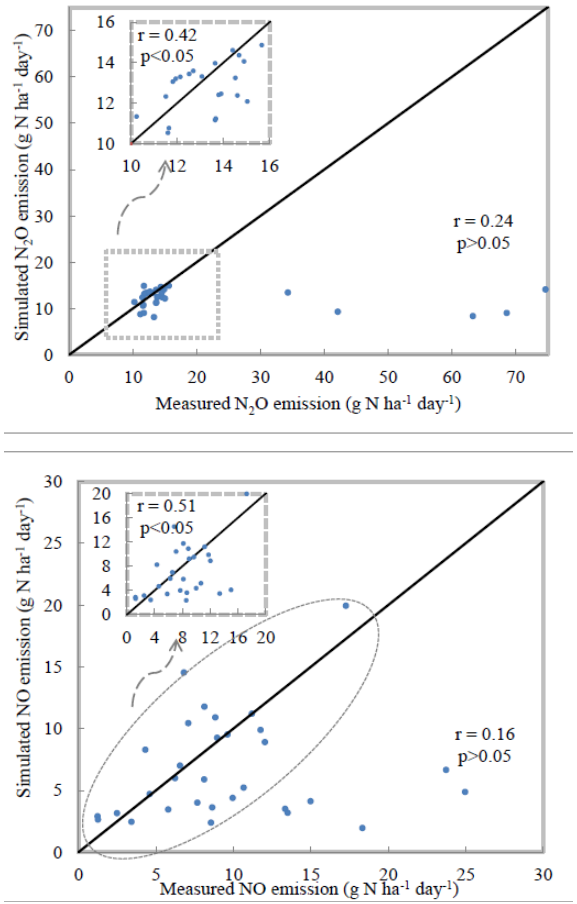

Fig. 5. Comparision of simulated and measured mean N_2O and NO emission for 31 sites in the Nyungwe forest.

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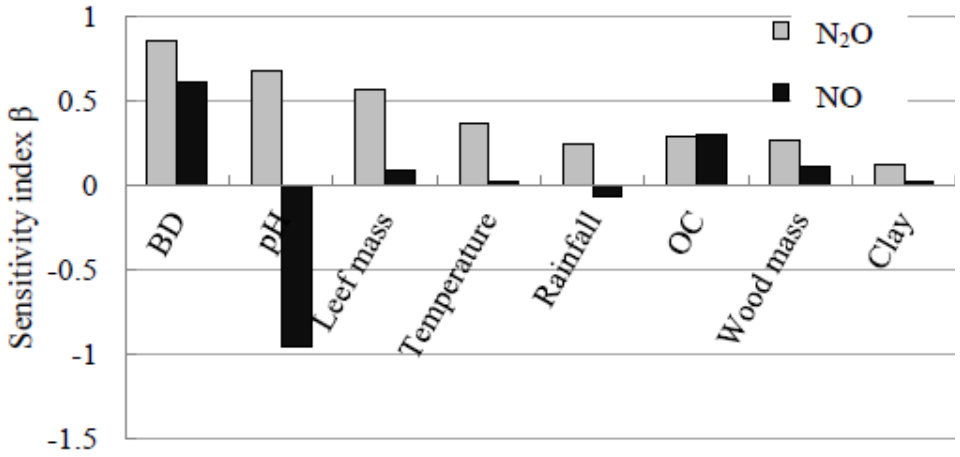

Fig. 6. Model sensitivity for changes of individual input parameters (±1 for pH, ±25 % for bulk density (BD) and ±50 % for other driving parameters) on N_2O and NO emissions.

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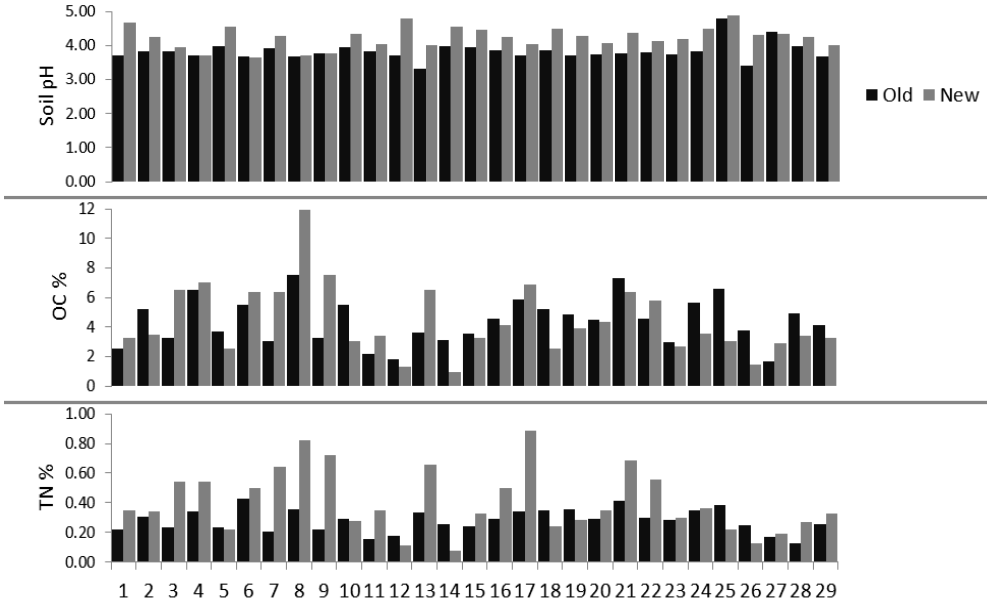

Fig. 7. Temporal variation of clay, organic carbon (OC), total nitrogen (TN) and pH values for 29 locations in the Nyungwe forest; "Old" and "New" indicate soil surveys in 1980's and 2009, respectively.

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