Response to anonymous referee #1 (Comments in black, Answers in blue, Suggested revisions in green)

General comments:

The paper under my reviewing addresses an important topic and contributes to improving the understanding of soil N_2O emissions from global land ecosystems. Overall, the authors have done a great job. They integrated soil nitrification-denitrification processes into the DGVM LPJ-GUESS model, clearly explaining and documenting the added mathematical formulations and parameters, although some complex processes were simplified during the development due to the "large-scale" model structure. Additionally, they examined the model's performance using a valuable site-level data set and quantified the environmental factors driving changes in global N_2O emissions among terrestrial ecosystems through model-based scenario analyses. I think this topic is interesting and of great relevance to GMD. The manuscript is in general well-written and easy to follow. However, a few pieces of information are missing, and some sections require minor adjustments before it can be accepted for publication. Below, I provide specific comments, which I hope will help further improve the manuscript.

We thank the reviewer for the expressed interest in our manuscript. In the revisions to the manuscript we will be addressing the raised questions as described below.

Specific comments:

The introduction is well stated. The description is sufficient to understand what has been developed in previous DGVM studies in terms of N_2O-related processes. However, the organization in some parts can be improved. LN65-66: 0.2-1.8% of what? Is it the proportion of N fertilization lost as N_2O?

Yes, '0.2-1.8%' is the percent of the N inputs, including the N applied as synthetic and organic fertilizer, crop residues, and the N deposited by grazing animals etc. To make it clear, "0.2-1.8%" will be revised to "0.2-1.8% of the N applied the soil" in the manuscript as suggested.

LN97-100: What specific cropland management practices are included in your model? How are these practices set up in the global simulations? Since conservation agriculture can significantly influence N_2O fluxes in the fields, even though most practices mitigate soil CO_2 emissions by enhancing soil C storage. It is better the specify the management setups somewhere in the methodology section.

At this moment, the cropland management practices implemented in LPJ-GUESS include tillage, crop residue retention, industrial N fertilizer and manure application, and cover cropping (both leguminous and non-leguminous). Given the widespread adoption of conventional practices in global agricultural soils, our large-scale simulations in this study assume that all croplands are managed with tillage and without cover cropping systems, with 25% of aboveground crop residue retained in the fields after harvest. Additionally, all crops receive time-dynamic N fertilizer and manure inputs over the years, with the timing of application varying by crop type.

We clarified the information on management practice setups in the first paragraph in Sect. 2.1 in the original manuscript: "Agricultural practices—such as tillage intensity, N mineral fertilizer and manure application, crop residue removal, and leguminous and non-leguminous cover crops—are also included (Ma et al., 2023; Olin et al., 2015b; Pugh et al., 2015). For large-scale application, to reflect the widespread adoption of conventional practices on current global agriculture (Porwollik et al., 2019), the model assumes that all croplands are under tillage management without cover cropping systems, and that 25% of aboveground crop residue is retained in the fields after harvest. Industrial N fertilizer is added to soils at three different stages of crop growth, with application rates varying by CFT. In contrast, all manure is applied as a single input at crop sowing to reflect the time required for manure N to become available for plant uptake in real-world practices (Olin et al., 2015b)."

Fig.1: In nitrification processes, where is the heterotrophic pathway? How do you consider this in the model depending on DON? This is an important process in acidic soils or environments where autotrophic nitrification is less dominant. It should be mentioned in the model description.

We agree with the reviewer that heterotrophic nitrification plays an important role in acidic soil environments. However, in this study, we consider only autotrophic nitrification, as it is the dominant pathway in most natural and agricultural soils (Chapin III et al., 2011). Additionally, modeling the heterotrophic pathway is more challenging because it requires estimating dissolved organic nitrogen (DON) as the main substrate for heterotrophic nitrifiers, and the relevant DON processes have not yet been implemented in LPJ-GUESS.

We will modify the information of heterotrophic nitrification in Sect. 2.2.2 in the revised manuscript. Suggested revision: "Autotrophic nitrification and heterotrophic nitrification are two distinct biological processes involved in the N transformation in soil ecosystems. We focused solely on representing autotrophic nitrification, which is the dominant process in most natural and agricultural soils (Chapin III et al., 2011). The heterotrophic pathway is also more challenging to model as it requires estimation of dissolved organic nitrogen as the main substrate for the responsible nitrifying bacteria."

LN191-195: Maybe the 38℃ is needed further discussion to represent the entire nitrification process, as NOB bacteria significantly favor higher temperatures compared to AOB and AOA.

True, as the reviewer mentioned, NOB bacteria significantly prefer higher temperatures than AOB and AOA. However, LPJ-GUESS currently does not simulate the growth and mortality of soil microbes, making it challenging to independently represent the temperature effects on different bacterial groups in the model.

We clarified this limitation in Sect. 2.2.2 in our original submission (Lines 182-184): "Due to the current limitation in the model's ability to simulate the growth and mortality of soil microbes, we integrate these two oxidation steps into one single process—i.e., NH_4^+ is oxidized to NO_3^- directly—to collectively represent nitrification in LPJ-GUESS (see Fig.1)."

In addition, to clarify, we will provide an explanation in the revised manuscript for why 38°C was chosen in Eq. 7. Suggested revision: "Soil temperature plays a crucial role in regulating microbial activities. For nitrite-oxidizing bacteria, 37–39°C is found to be optimal for substrate oxidation (Taylor et al., 2019) and for ammonia-oxidizing bacteria and archaea the optimal soil temperature can range from 31–42°C (Ouyang et al., 2017). In the model, the maximum nitrification rate is thus assumed to occur at 38°C, as the average optimal temperature for these three groups of nitrifiers."

LN420-424: It would be valuable to compare crop yields (or N use efficiency). For instance, in the high N fertilization scenario, was the modelled yield lower than the observed yield? If so, this could suggest that less N was taken up, resulting in less N removal from the system and leaving more N to be emitted as N_2O.

Good point. We did not compare the yield in this study, but did it in our previous studies (see Ma et al., 2022a; Ma et al., 2023). The model generally generates lower yields than observations at the high fertilizer levels, likely resulting in excess reactive N remaining in the soils and higher N_2O loss.

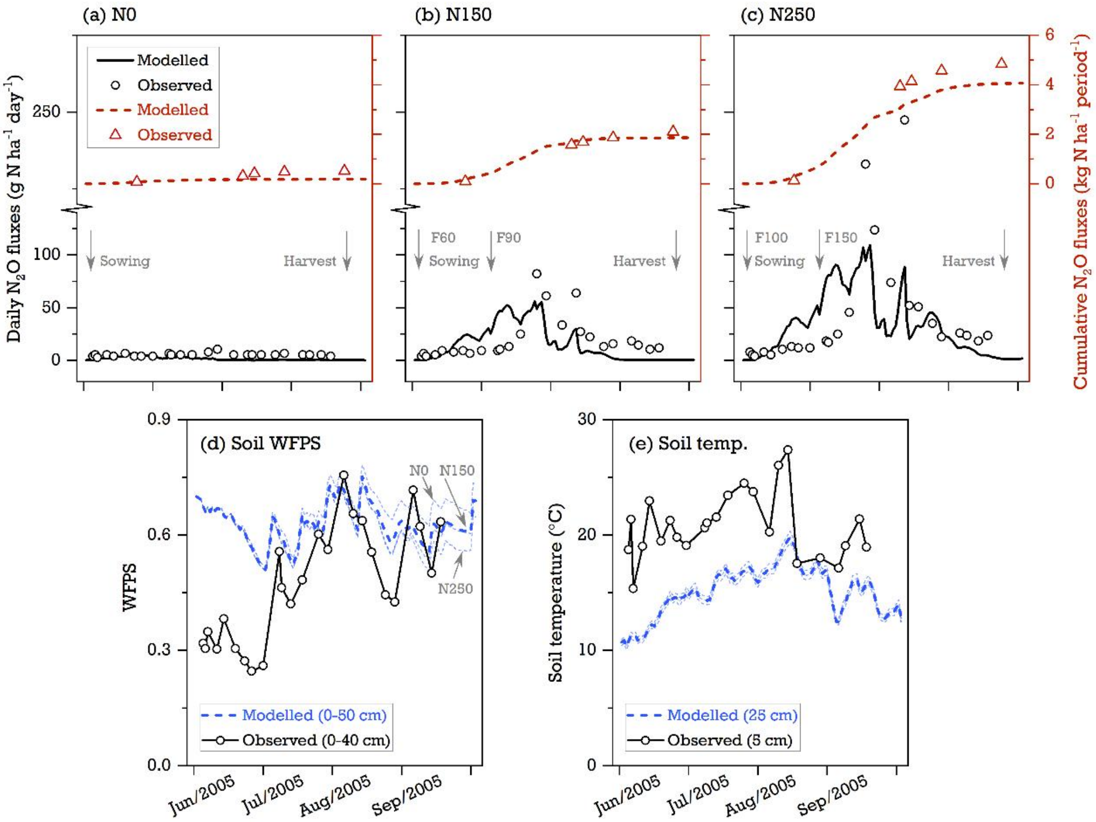
We have discussed this in the first paragraph in Sect. 4.1 in the original manuscript (Lines 576-583): "In previous studies (Ma et al., 2022a, 2023) crop yields simulated by LPJ-GUESS under high N fertilizer inputs were lower than observations, indicating an underestimation of both plant N demand and uptake. Consequently, the excess N remaining in the soil would facilitate higher gaseous loss in the model. This can also explain the significant overestimations on cumulative N_2O emissions in rice cropping systems (Fig. 3), where the simulated growing season was about one month shorter than field experiments since the growth phase between rice sowing and transplanting has not been implemented in LPJ-GUESS. Compared to observations, such a reduction in the simulated growing period was expected to produce lower N uptake and higher N_2O emissions."

LN450-453: I would suggest to add the observed WFPS to Fig. S3 to clearly compare the mismatch between the simulation and observation, if the reported data are available.

We understand the reviewer's concerns regarding the comparison of modeled and observed soil moisture at the site level. Unfortunately, the reported WFPS at the three field sites in Fig. S3 is not consistently available throughout the experimental periods. For instance, at Tapajós National Forest in Brazil (Fig. S3a; Davidson et al., 2008), only volumetric soil water content at a depth of 2 m was reported, which cannot be directly compared with the simulated WFPS at 0.5 m. At the temperate forest in Japan (Fig. S3b; Morishita et al., 2007), no observed soil moisture data were available. For the semi-arid grassland in China (Fig. S3c; Du et al., 2006), only a few monthly (seasonal) WFPS values were reported for 1998 (2001), despite the total experimental period lasting five years. Accordingly, it is challenging to add the observed WFPS to Fig. S3.

LN482-484 and Fig.5d: It could be interesting to identify which thin-dashed blue WFPS corresponds to each N treatment. Does the N250 scenario, with the highest N, use the most water in the soil?

Yes, in the model, crops with the highest N250 input consume the most soil water, resulting in the lowest remaining WFPS in the soil. As the reviewer suggested, we will clearly label the thin-dashed blue WFPS line for each N treatment in Fig. 5d, which will be updated accordingly in the revised manuscript as below:



LN545-547: It seems to find an explanation for the reduced N_2O emissions under elevated CO_2 concentrations.

In LPJ-GUESS, rising CO_2 levels in the atmosphere reduce the simulated N_2O emissions primarily due to increased plant N uptake (see Fig. S5). The reduced N remaining in the soil leads to lower gaseous N emissions to the atmosphere.

We gave an in-depth discussion in the fourth paragraph in Sect. 4.2 in our original manuscript: “It remains unclear which of these two opposing mechanisms might play a more dominant role in field measurements, but the negative CO_2 effect on N_2O emissions, at least in our simulations (-87% during 2011-2020 on global natural lands; Fig. 8), can be explained by enhanced vegetation N uptake and reduced soil mineral N surplus under increased CO_2 conditions (Fig. S5 in Supporting Information). Studies using other models have shown similar results (e.g., Huang and Gerber, 2015; Tian et al., 2019; Zaehle et al., 2011).”

LN651-660: For large-scale applications, fertilizer type-usually simplified as the ratio of NH4 to NO3 in the model-is one of the factors contributing to the simulated uncertainty in N2O emissions. Does LPJ-GUESS actually account for this when performing the S5 runs ("Const_Nfert")?

We agree with the reviewer's opinion that fertilizer type significantly affects the uncertainty in simulated N_2O fluxes, as soil NH4 and NO3 are essential substrates for nitrifying and denitrifying bacteria that regulate N_2O production. Currently, LPJ-GUESS does not distinguish between different fertilizer types and assume a fixed 1:1 ratio of NH4 to NO3 for all N fertilizer inputs.

We will bring this limitation to Sect. 4.3 for discussion: "In addition, concentrations of soil NH_4^+ and NO_3^-, as essential substrates for nitrifying and denitrifying bacteria, are dominant factors controlling N_2O productions on agricultural lands (Fig. 1). The ratio of NH_4^+ to NO_3^-, which typically varies with fertilizer types, has been reported to significantly influence soil N_2O emissions in field experiments (e.g., Nelissen et al., 2014; Shcherbak et al., 2014). Globally, Nishina et al. (2017) and Tian et al. (2022) pointed out that the NH_4^+:NO_3^- ratio from N fertilizer application gradually increased from 2.0 to 7.0 during 1961–2010 as a result of the increased consumption of urea on croplands. In contrast, LPJ-GUESS assumed this ratio as a constant of 1.0 when agricultural soils received N fertilizer inputs. Using this fixed parameter in our simulations cannot reflect the variability of fertilizer-type-induced N_2O emissions in reality, particularly in highly fertilized regions."

References

Chapin III, F. S., Matson, P. A. and Vitousek, P. M.: Principles of Terrestrial Ecosystem Ecology, Second Edi., Springer Science and Business Media, New York, USA., 2011.

Davidson, E. A., Nepstad, D. C., Ishida, F. Y. and Brando, P. M.: Effects of an experimental drought and recovery on soil emissions of carbon dioxide, methane, nitrous oxide, and nitric oxide in a moist tropical forest, Glob. Chang. Biol., 14(11), 2582–2590, doi:10.1111/j.1365-2486.2008.01694.x, 2008.

Du, R., Lu, D. and Wang, G.: Diurnal, seasonal, and inter-annual variations of N2O fluxes from native semi-arid grassland soils of inner Mongolia, Soil Biol. Biochem., 38(12), 3474–3482, doi:10.1016/j.soilbio.2006.06.012, 2006.

Huang, Y. and Gerber, S.: Global soil nitrous oxide emissions in a dynamic carbon-nitrogen model, Biogeosciences, 12(21), 6405–6427, doi:10.5194/bg-12-6405-2015, 2015.

Ma, J., Olin, S., Anthoni, P., Rabin, S. S., Bayer, A. D., Nyawira, S. S. and Arneth, A.: Modeling symbiotic biological nitrogen fixation in grain legumes globally with LPJ-GUESS (v4.0 , r10285), Geosci. Model Dev., 15(2), 815–839, doi:10.5194/gmd-15-815-2022, 2022a.

Ma, J., Anthoni, P., Olin, S., Rabin, S. S., Bayer, A. D., Xia, L. and Arneth, A.: Estimating the global influence of cover crops on ecosystem service indicators in croplands with the LPJ-GUESS model, Earth's Futur., 11(5), doi:10.1029/2022EF003142, 2023.

Morishita, T., Sakata, T., Takahashi, M., Ishizuka, S., Mizoguchi, T., Inagaki, Y., Terazawa, K., Sawata, S., Igarashi, M., Yasuda, H., Koyama, Y., Suzuki, Y., Toyota, N., Muro, M., Kinjo, M., Yamamoto, H., Ashiya, D., Kanazawa, Y., Hashimoto, T. and Umata, H.: Methane uptake and nitrous oxide emission in Japanese forest soils and their relationship to soil and vegetation types, Soil Sci. Plant Nutr., 53(5), 678–691, doi:10.1111/j.1747-0765.2007.00181.x, 2007.

Nelissen, V., Saha, B. K., Ruysschaert, G. and Boeckx, P.: Effect of different biochar and fertilizer types on N2O and NO emissions, Soil Biol. Biochem., 70, 244–255, doi:10.1016/j.soilbio.2013.12.026, 2014.

Nishina, K., Ito, A., Hanasaki, N. and Hayashi, S.: Reconstruction of spatially detailed global map of NH4+ and NO3application in synthetic nitrogen fertilizer, Earth Syst. Sci. Data, 9(1), 149–162, doi:10.5194/essd-9-149-2017, 2017.

Olin, S., Lindeskog, M., Pugh, T. A. M., Schurgers, G., Wårlind, D., Mishurov, M., Zaehle, S., Stocker, B. D., Smith, B. and Arneth, A.: Soil carbon management in large-scale Earth system modelling: Implications for crop yields and nitrogen leaching, Earth Syst. Dyn., 6(2), 745–768, doi:10.5194/esd-6-745-2015, 2015b.

Ouyang, Y., Norton, J. M. and Stark, J. M.: Ammonium availability and temperature control contributions of ammonia oxidizing bacteria and archaea to nitrification in an agricultural soil, Soil Biol. Biochem., 113, 161–172, doi:10.1016/j.soilbio.2017.06.010, 2017.

Porwollik, V., Rolinski, S., Heinke, J. and Müller, C.: Generating a rule-based global gridded tillage dataset, Earth Syst. Sci. Data, 11, 823–843, doi:10.5194/essd-11-823-2019, 2019.

Pugh, T. A. M., Arneth, A., Olin, S., Ahlström, A., Bayer, A. D., Klein Goldewijk, K., Lindeskog, M. and Schurgers, G.: Simulated carbon emissions from land-use change are substantially enhanced by accounting for agricultural management, Environ. Res. Lett., 10(12), doi:10.1088/1748-9326/10/12/124008, 2015.

Shcherbak, I., Millar, N. and Robertson, G. P.: Global metaanalysis of the nonlinear response of soil nitrous oxide (N2O) emissions to fertilizer nitrogen, Proc. Natl. Acad. Sci. U. S. A., 111(25), 9199–9204, doi:10.1073/pnas.1322434111, 2014.

Taylor, A. E., Myrold, D. D. and Bottomley, P. J.: Temperature affects the kinetics of nitrite oxidation and nitrification coupling in four agricultural soils, Soil Biol. Biochem., 136(December 2018), 107523, doi:10.1016/j.soilbio.2019.107523, 2019.

Tian, H., Yang, J., Xu, R., Lu, C., Canadell, J. G., Davidson, E. A., Jackson, R. B., Arneth, A., Chang, J., Ciais, P., Gerber, S., Ito, A., Joos, F., Lienert, S., Messina, P., Olin, S., Pan, S., Peng, C., Saikawa, E., Thompson, R. L., Vuichard, N., Winiwarter, W., Zaehle, S. and Zhang, B.: Global soil nitrous oxide emissions since the preindustrial era estimated by an ensemble of terrestrial biosphere models: Magnitude, attribution, and uncertainty, Glob. Chang. Biol., 25(2), 640–659, doi:10.1111/gcb.14514, 2019.

Tian, H., Bian, Z., Shi, H., Qin, X., Pan, N., Lu, C., Pan, S., Tubiello, F. N., Chang, J., Conchedda, G., Liu, J., Mueller, N., Nishina, K., Xu, R., Yang, J., You, L. and Zhang, B.: History of anthropogenic Nitrogen inputs (HaNi) to the terrestrial biosphere: a 5 arcmin resolution annual dataset from 1860 to 2019, Earth Syst. Sci. Data, 14(10), 4551–4568, doi:10.5194/essd-14-4551-2022, 2022.

Zaehle, S., Ciais, P., Friend, A. D. and Prieur, V.: Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions, Nat. Geosci., 4(9), 601–605, doi:10.1038/ngeo1207, 2011.