Potential of carbon uptake and local aerosol production in boreal and hemi-boreal ecosystems across Finland and in Estonia

Piaopiao Ke et al., 2025

General comments

This manuscript was well revised according to reviewer's comment. Authors tried to answer to the question reviewers raised and refine the manuscript. It becomes readable easily compared to the previous version. Very appreciated.

Despite author's great efforts, the conclusion, readers can get through this manuscript, still seems to be very simple. Unique part in this manuscript is authors used two different data set with CO_2 flux and aerosols. However, the conclusion might not include those data enough. It doesn't mean that experiment results are not enough. I believe all data and experimental setting are quite good enough.

Authors' conclusion is *"Overall, considering the large area of forests in Finland and Estonia, the forests in total have the largest potential of climate cooling when considering the CO_2 uptake and local new particle formation.".* There are three points. 1) large area 2) CO_2 uptake 3) local new particle formation. First, authors never discussed that land size is one of factors in the manuscript. It should be re-considered whether it is valuable to make a point with the land size here. Authors explained the agriculture field is comparable to forest for CO_2 uptake during summer and high N_{neg} was observed. Based on this result, readers can assume that agricultural field can be an option for climate change policy. If not, authors should answer to the question, why forest is more important than agriculture fields with a new finding based on two different data. This is well known fact that forest CO_2 sink/summertime CO_2 sink is stronger than other areas (such as urban garden, agriculture and coastal site) and other seasons based on many of previous papers.

If the conclusion ends up with that forest is the best place for climate change policy with common knowledges, this manuscript cannot be valuable to be published.

Authors should re-consider and explain major points such as how all data sets are used to make conclusion (all data can be linked together) and what the new findings are here when two data sets are used. And then it can be considered to be published.

We appreciate your careful and thorough reviewing of the manuscript very much. We agree that the conclusion should be revised to be more explicit. Both the land size and single site' potential are important in our study. We now have revised the Section 3.3 and Conclusion to address the following points:

- Momentary CO2 uptake rate and local aerosol production: We have clarified that "our results showed that agricultural fields have highest potential to contribute to momentary CO_2 uptake and aerosol formation, affected by their vegetation and management practices. However, carbon inputs from fertilization and removal through

harvested biomass in agricultural fields, which were not considered in our study, can lead to net carbon emissions in the annual carbon budgets (Heimsch et al., 2021; and references therein)" (Lines 442-446). This is the most unexpected results from our study, indicating that agricultural sites have both high momentary CO_2 uptake and local aerosol production. However, it should be noted that the momentary CO_2 uptake is only one part of the whole carbon budget of an agricultural field.

- Large area: We have added a detailed discussion on the significance of land size in the context of discussing different ecosystems' cooling potential via CO_2 uptake and aerosol production, "Moreover, forests are the dominant landscape in Finland, covering ~9 times the area of agricultural fields (Table 2). Considering their large area, boreal forests in Finland are likely the largest contributor of climate cooling when considering the CO_2 uptake and local new particle formation" (Lines 446-469). In the Conclusion, it was revised to "Overall, considering the large area of forests in Finland and Estonia, the forests in total are the largest contributors to climate cooling in terms of their CO2 uptake and local new particle formation" (Line 526). It is important to point out that in present days, forests are still the largest contributor to climate cooling in Finland, providing a comprehensive conclusion of the comparison between different ecosystems.

The direct connection between NEE and N_{neg} was weak at each site (see example picture below for Hyytiälä forest in summer, when the photosynthetic photon flux density is higher than 600 µmol m^{-2} s^{-1}. The 10th, 25th, 50th, 75th, and 90th percentile of N_{neg} in each NEE bin were plotted). This suggests that the momentary carbon uptake and aerosol forming potential of the ecosystems investigated here are weakly coupled to each other, despite the theoretical connection. However, it is important to recognize that both carbon uptake and aerosol formation are essential processes for ecosystems to contribute to climate cooling. Our results compared the carbon uptake and aerosol formation potential across different ecosystems. Quantifying the potential connection between the carbon uptake and aerosol forming potential of ecosystems requires a deeper analysis with careful consideration of the meteorological and other factors influencing these two processes, which is beyond the scope of the present manuscript and will be investigated in follow-up studies.

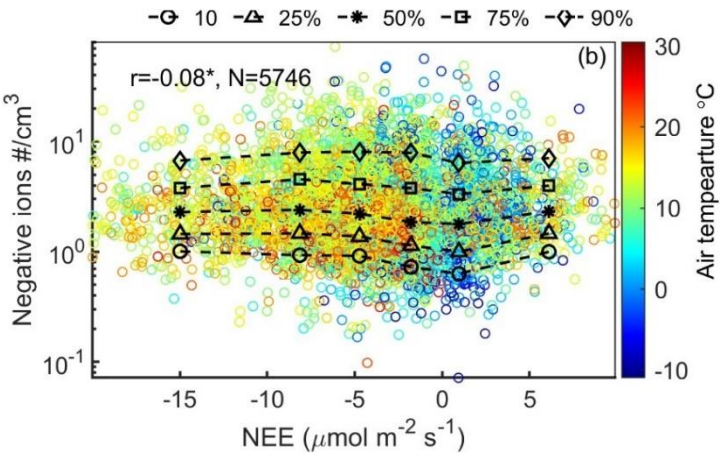

Figure example1. The correlation between NEE and N_{neg} at Hyytiälä forest in summer. Half-hour mean data are used.

Another pathway to link the two datasets in this study can be comparing their relative contributions to radiative forcing, as done in the study by Weber et al. (2024). However, the process of aerosol growth, the radiation scattering effect, and aerosol-cloud interactions take place on a regional scale, whereas we aim to emphasize here the ecosystem-scale potentials of CO_2 uptake and aerosol production. We do this by utilizing the datasets of negative ions in specific size range, 2-2.3 nm. This is novel in our work and allows us to quantify ecosystems' climate cooling potential regarding aerosol production with a simplified method. How the ecosystem-scale CO_2 uptake and aerosol production impact the regional climate remains a topic to be addressed in the future studies.

We have now provided a more comprehensive and nuanced conclusion. We hope these revisions address the reviewer's concerns well and the present manuscript meets the standard of publication.

Minor comments

1. Reference station/reference data: It is still unclear to define Hyytiälä forest (FHYY) as a reference site. When we think of a reference site (background site) for CO2 flux, it might be chosen by environments without any variation/fluctuations like costal site (see Figure 4). It is hard to understand the reason to choose F-HYY as a reference site. It should also be noted that here the "reference site" is not taken as a background information site to investigate the effects of some disturbances/management practices/pollutions. It is simply applied for easier comparison between each ecosystem. To make it clearer, we revised the text to "The value of NEE and N_{neg} at the boreal forest in Hyytiälä (F-HYY) were used as references, to which NEE and N_{neg} at all other sites were compared" (Line 393). Forests are the largest types of land cover in Finland (Table 2). Also, F-HYY has the longest record of data and endures relatively little anthropogenic interference (Line 194). The costal sites still presented seasonal changes in NEE and N_{neg}, although the seasonal changes were in a much smaller

magnitude than that in other ecosystems. And also, the dataset at that site was one-year long, and the inter-year change can drive evident variation in its NEE and local aerosol production values.

2. Height of each station: When seeing table S1, the instrument heights were quite different from each other. This can make a bias to analyse NEE when their values were compared to each other. Is it enough to explain that the height can be represented each site characteristic?

   The measurement height for NEE is all above the canopy height of each terrestrial ecosystem, while the NAIS is all 1-2 m above ground at all studied sites (Line 147). To avoid confusion, we added canopy height to Table S1 now. The measurement height for eddy covariance at each station was carefully selected to represent the whole ecosystem (Järvi et al., 2012; Alekseychik et al., 2021; Heimsch et al., 2021; Laurila et al., 2021). At the height of 3 m, 80% of the footprint of the eddy covariance measurements covered an area with a radius 100 m (Alekseychik et al., 2021). The NEE at Qvidja, which has the lowest measurement height of NEE, 2.3 m, the data were discarded when the flux footprint was not sufficiently representative of the target grassland (Heimsch et al., 2021; Line 212). Hence the measured NEE at each station can sufficiently represent the site characteristics. Although the footprint at taller measurement heights covered a larger area, as long as the main area constrained for the ecosystem, the measured NEE can still represent the whole ecosystem.

3. Figure 7: no explanation of a) in the caption.

   Revised to "Figure 7. The 50th (a) and 75th percentile (b) of negative intermediate ions (N_{neg}) at 2.0-2.3 nm at each hour and the daily fluctuations of N_{neg} (c) for the agricultural fields in spring (MAM) and the corresponding 50th percentile, 75th percentile and normalized concentration for median values, (d), (e), (f), in summer (JJA), respectively".

4. Figure 9: If the error bars mean 10th and 25th percentile for NEE, is it necessary to + and – value? It is hard to understand of the graph. Also, there is no explanation of a) to c) in the caption and even in the manuscript.

   The caption was revised now as "Figure 9. Comparison of NEE and negative intermediate ions at 2.0-2.3 nm (a), NEE and air temperature (b), and negative intermediate ions at 2.0-2.3 nm and air temperature (c) across different sites. The dots represent median values during summer midday (10:00-14:00). Error bars indicate the 10th and 25th percentiles for NEE, and the 75th and 90th percentiles for negative intermediate ions and air temperature, reflecting the CO_2 uptake rate and aerosol formation under optimal conditions". We focused on the potential of ecosystem CO_2 uptake and aerosol production, i.e., how these will be under optimal conditions. Hence, the 90% and 75% of N_{neg} and 10% and 25% for NEE were kept. It is not a graph that is very direct, and we revised the caption to make it easier to understand.

Reference:

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