Anonymous Referee #1, 28 Spe 2024

The authors analyzed and presented the net ecosystem exchange (NEE) and the number concentration of negative intermediate ions (N_{neg}) measurements across sites in different ecosystems. They introduced the novel framework "CarbonSink + Potential" to highlight the importance of boreal ecosystems in the climate system. This framework offers an interesting and new perspective on how boreal ecosystems directly absorb CO_2 and indirectly influence the radiation balance, thereby mitigating global warming and climate change.

We thank the reviewer for the positive and constructive evaluation of our manuscript. All comments are addressed below and greatly helped to improve our manuscript.

We would like to make a note that we have corrected the measurement period at Haltiala croplands to ‘06/2021-10/2022’ from ‘01/2022-12/2022’. All available data for both NAIS and CO_2 fluxes at Haltiala cropland are from 2021/06-2022/10 so far. We modified the text and the code so now it is the right date range. After revision, the midday CO_2 uptake rate and N_{neg} in summer in Haltiala cropland decreased from 19.69 µmol m^{-2} s^{-1} and 3.08 cm^{-3} to 10.42 µmol m^{-2} s^{-1} and 2.66 # cm^{-3}, respectively. The related figures and figures were all revised. However, the main conclusions remained without changes. Detailed responses to the comments can be found below.

This topic is both significant and relevant to the scope of Biogeoscience. While the paper is generally well-written, the analysis remains preliminary, and the main argument lacks clarity. I believe further analysis is needed to enhance the overall quality of manuscript. Here are some major comments I have:

1. I suggest that the authors change the way they present the data. Figures 2-4 and Figures 6-8 show two series of data for NEE and N_{neg}, respectively. I wonder why the authors presented the mean, 25th, and 50th percentiles for NEE (and the 50th and 75th percentiles for N_{neg}) separately in different panels. There are other effective options, such as box plots or violin plots. Additionally, could you combine the results for the different ecosystems? This could make it easier to see the differences between the ecosystems.

Reply: Thank you for the suggestion. In box plots (see examples below), the information is clustered together, making it too messy to include all ecosystems also in the same figure. As the main aim is to present the potential of CO_2 uptake (50th and 25th percentile) and aerosol production (50th and 75th percentile), we would prefer the original way of presenting the data. However, if the editor or reviewers insist, we can change the way of presenting the results.

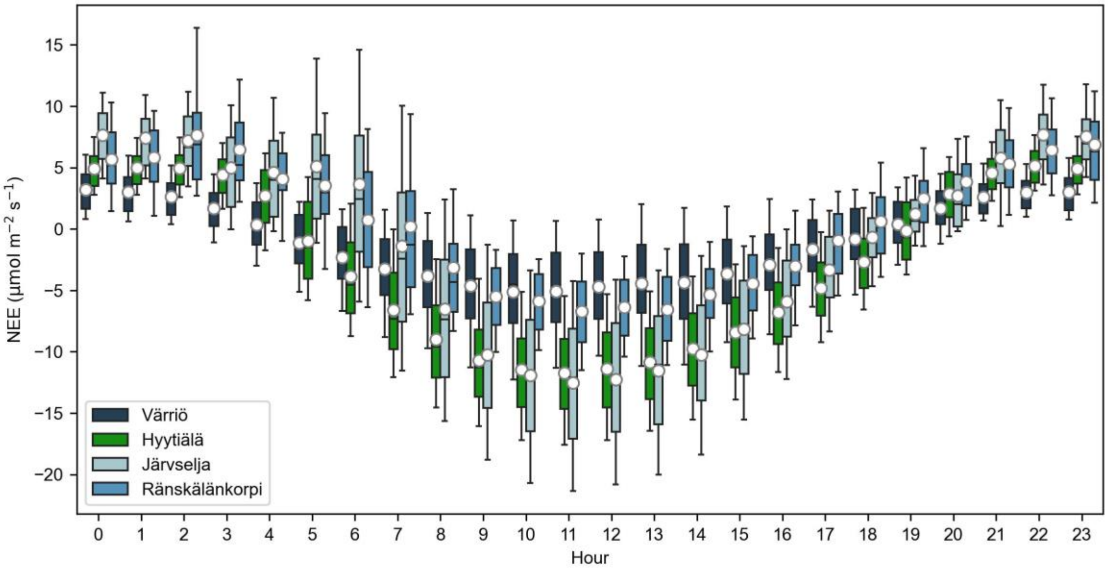

Figure example1. The diurnal plot of the NEE in summer. The circles are mean values and the lines in the boxes are median values.

It is an interesting approach to consider the role of terrestrial ecosystems as direct carbon sinks and indirect sources of new particle precursors and aerosols. However, the comparison conducted in this study did not integrate these two concepts very well. For example, a recent study by Weber et al. (2024) illustrated this integration effectively. I wonder if the authors could provide an estimation of the relative importance of these two concepts.

Reply: The relative importance of CO_2 uptake and aerosol production can be compared by their contribution 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 a follow-up study.

2. Most of the analysis in this study is based on the diurnal cycle, but it lacks depth in data interpretation. I suggest conducting further analysis to provide more insights. For example, different ecosystems exhibit distinct terpenoid emission patterns. Many boreal needleleaf

forest ecosystems are dominated by monoterpenes (Boy et al., 2022), which are important precursors for particles. However, the fen at the Siikaneva site also has high isoprene emissions (Vettikkat et al., 2023), which could suppress the formation of new particles (Kiendler-Scharr et al., 2009). In addition, Vettikkat et al. (2023) reported high temperature sensitivity of terpenoids. I noticed that meteorological data was mentioned in Section 2.2 of the paper, but I did not see any related analysis. Could the authors incorporate additional analysis using meteorological data? For instance, how does N_{neg} respond to temperature changes? How do different vegetation components or types affect the NEE and N_{neg}?

Reply: It is true that different ecosystems may exhibit distinct terpenoid emission patterns and show different responses to temperature and radiation, which can further influence aerosol production. However, the responses of N_{neg} (aerosol production) and NEE to air temperature did not present a uniform trend and it is difficult to tell how different ecosystems respond differently to air temperature changes.

For example, when the PPFD is between 400 and 800 μmol m^{-2} s^{-1} in summer (figures below), there is a slight decreasing trend of N_{neg} with increasing air temperature for sites other than Hyytiälä forest, which may be related to the cluster stability. In the case of NEE, all forest sites showed an increasing trend with air temperature, in contrast to the Siikaneva peatland. However, all the correlations were weak ($R< 0.3$). Air temperature can both increase the rates of respiration and photosynthesis, which makes it quite site-specific whether NEE (net CO_2 flux) will increase or decrease with air temperature. For N_{neg}, other factors, such as H_2SO_4 concentration, can distinctly impact the clustering formation. As the plots did not help to address our main research questions, we are not including them in the manuscript.

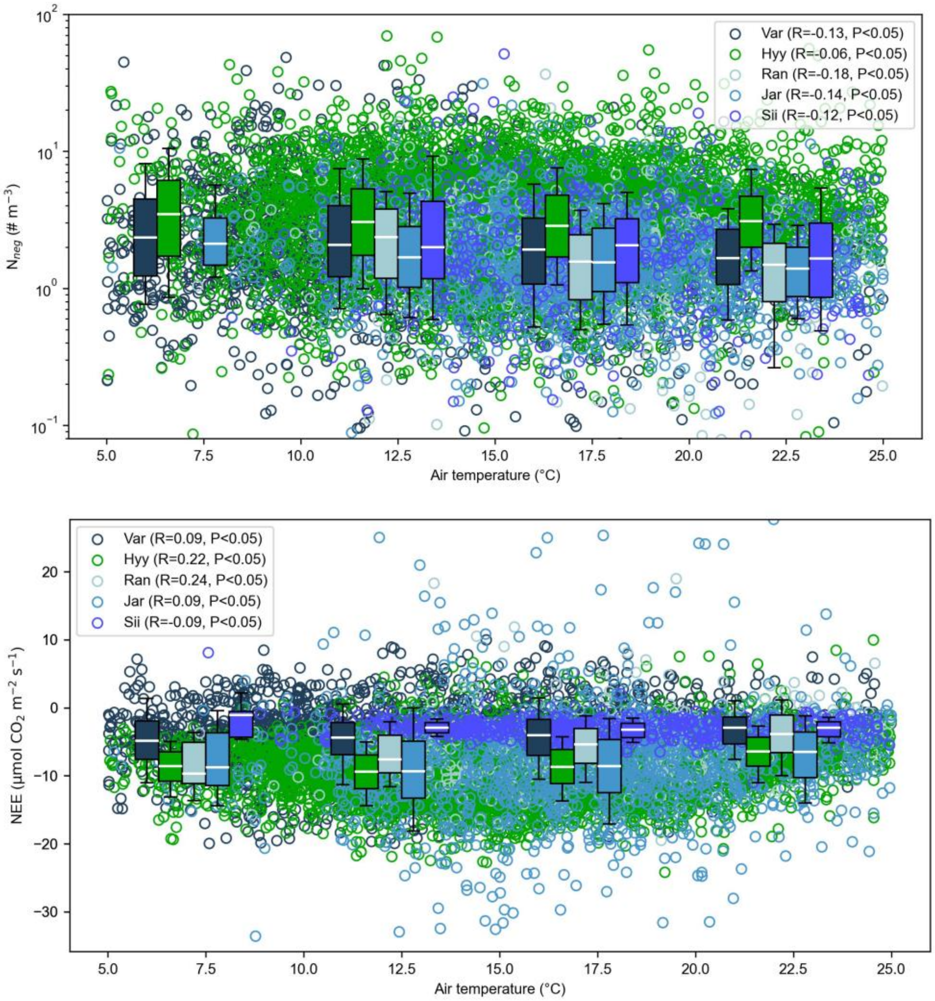

Figure example2: The responses of N_{neg} and NEE to air temperature in summer when the photosynthetic photon flux density (PPFD) is between 400 and 800 μmol m^{-2} s^{-1}. Half-hourly mean data are presented. The boxes are distributions of N_{neg} and NEE in each air temperature bins of 5-10, 10-15, 15-20, 20-25°C.

We now have revised Figure 9 and added two paragraphs (lines 396-426), briefly reasoning why we see different NEE and N_{neg} across the studied ecosystems. This included the analysis of air temperature and radiation:

"Multiple factors can cause the difference in NEE and N_{neg} across the sites despite the similar seasonal and diurnal variation patterns. The CO_2 uptake rate at midday in summer increased with an increasing air temperature in both studied forests and agricultural fields (Figure 9). Moreover, the CO_2 uptake rate at midday in summer increased with LAI across the studied forest ecosystems (Table 1 and Figure S9). As F-RAN was selectively harvested (Section 2.3), the leaf area was decreased, which can result in a lower CO_2 uptake rate than other forests under similar air temperature and PPFD. Additionally, the peat soil at F-JAR and F-RAN can induce higher respiration (Figure 2). Hence, even though the LAI and air temperature at F-JAR were 23% and 10% higher than that in F-HYY, respectively, the NEE at F-JAR was only 4% lower than that at F-HYY. In the agricultural fields, the LAI and air temperature were comparable or higher than that in the forests, which may explain the high momentary CO_2 uptake rate at summer midday in the agricultural fields.

In the case of N_{neg}, the precursor of aerosol production largely influences N_{neg}. The trends of N_{neg} varying with air temperature and radiation were not evident (Figures 9 and S9). H_2SO_4 formation can drive the nucleation process and is influenced by the sulphur dioxide concentration and radiation. As the garden area and agricultural fields in this study are located in or nearby cities, the SO_2 concentration there may be enhanced due to the anthropogenic pollution and its long-range transport. Also, the terpene emissions can initiate NPF, which has been observed in Siikaneva peatland and led to stronger NPF there than that in F-HYY (Junninen et al., 2022; Huang et al., 2024). However, these events were reported to occur mostly in the late evening. Different plant species can emit different types of BVOCs (Guenther et al, 2012), e.g., monoterpenes are found dominant in coniferous forests and isoprene dominant in broadleaf forests. The oxidation products of monoterpenes can enhance aerosol formation and growth (Rose et al., 2018), while isoprene has been reported to inhibit new particle formation (Kiendler-Scharr et al., 2009). As birch species are mixed with coniferous species in F-JAR, the possibly higher isoprene emission than in the other three predominantly coniferous forests may partially explain the lower N_{neg} in F-JAR. Moreover, the enhanced NH_3 in agricultural fields can play a synergistic role with both H_2SO_4 and low volatile organic compounds in clustering (Dada et al., 2023), which may explain the generally high N_{neg} in the three studied agricultural fields."

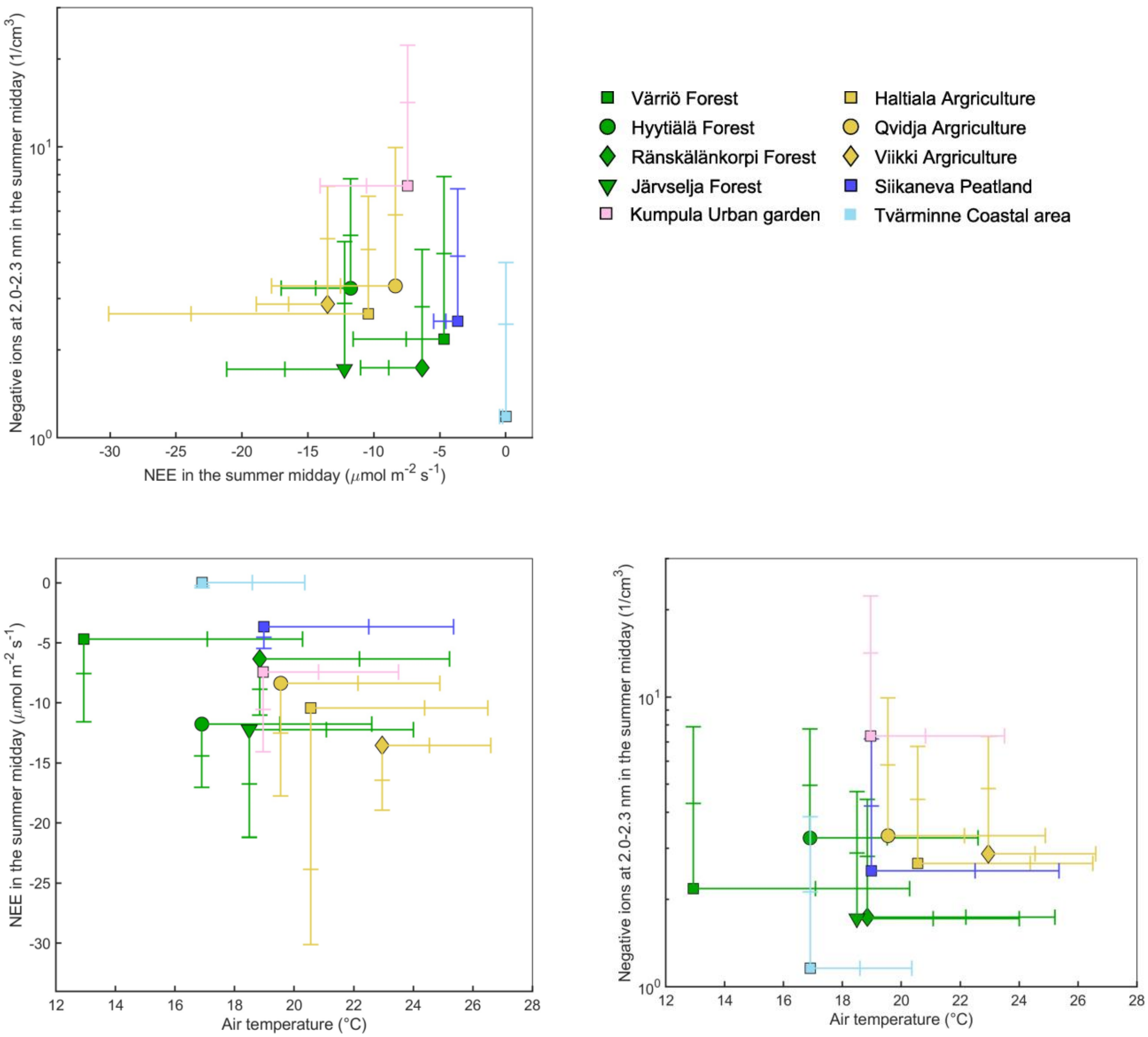

Figure 9. Comparison between median NEE, median negative intermediate ions at 2.0-2.3 nm, and median air temperature at midday in summer between the sites. The error bars are 10^{th} and 25^{th} percentile for NEE, 75^{th} and 90^{th} percentile for the negative intermediate ions, and 75^{th} and 90^{th} percentile for the air temperature at each site.

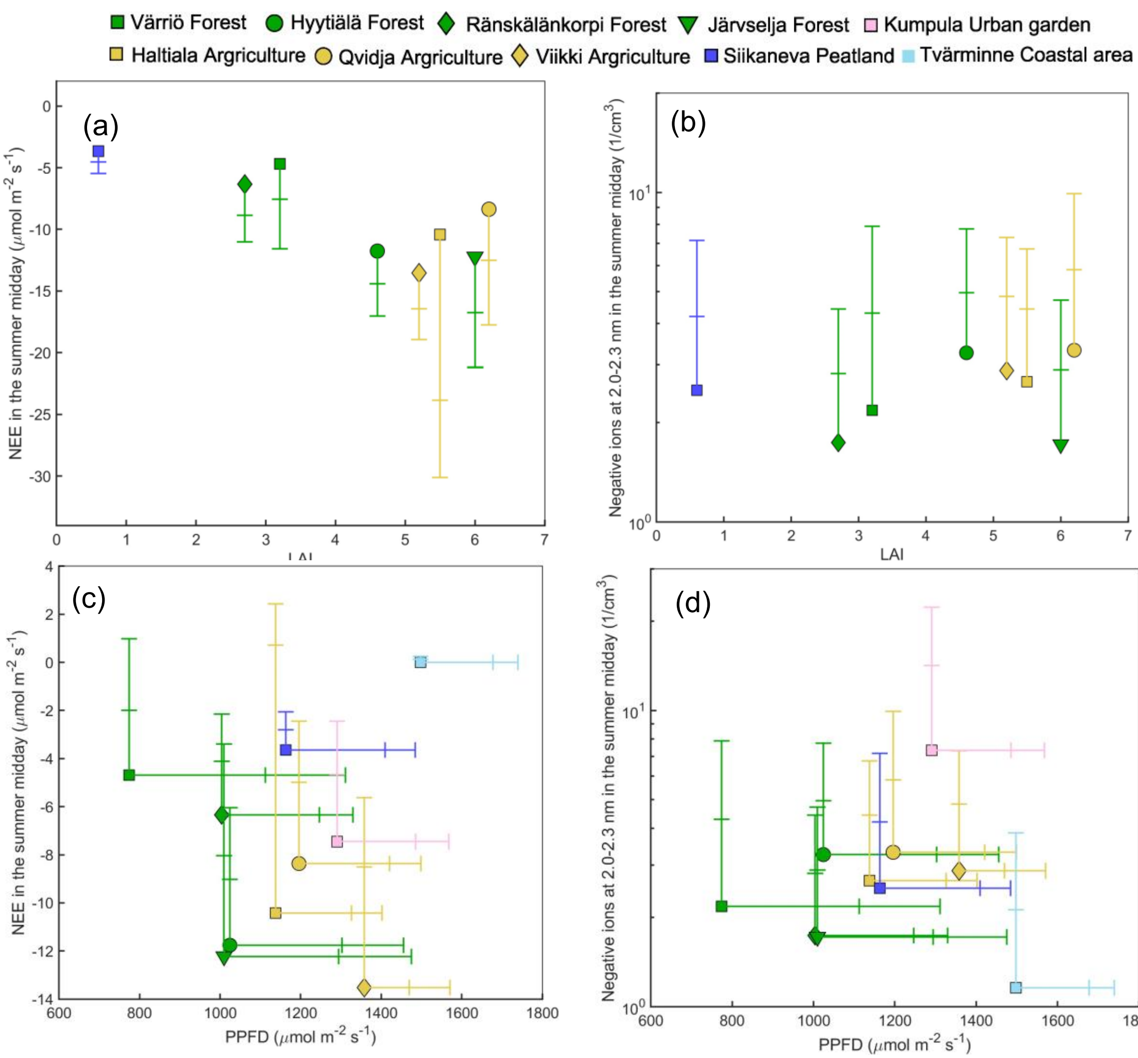

Figure S9. Comparison between median NEE, median negative intermediate ions at 2.0-2.3 nm, leaf area index, and median photosynthetic photo flux density (PPFD) at midday in summer between the sites. The error bars are 10th and 25th percentile for NEE, 75th and 90th percentile for the negative intermediate ions, and 75th and 90th percentile for PPFD at each site.

Minor comments:

Line 180: The data periods differ among sites. Although the authors claimed that they would not discuss inter-annual variation, data from shorter periods, especially as short as one year, will still be affected by it, which may affect their diurnal cycles and comparisons with other sites. I think the authors should aware this and demonstrate the potential impact of inter-annual variation on their analysis.

Reply: We now have added the standard deviation of NEE and N_{neg} at summer midday for all measurement years in Table 2 and discussed the potential impact of inter-annual variation on the result in lines 386-395 “It should be noted that only 1 year of data were applied in the stations with newly established atmospheric measurement, i.e., C-TVA and A-VII, although measurements continue. The inter-annual variation of NEE has been widely observed in many ecosystems, e.g., F-HYY (Neefjes et al., 2022) and A-QVI (Heimsch et al., 2021), possibly due to inter-annual change in temperature and precipitation. In the reported year in C-TVA and A-VII, the air temperature was higher than average in years 2015-2020 (Finnish Meteorological Institute; Figure S8). Since a higher air temperature can simultaneously increase the rates of respiration and photosynthesis in an ecosystem, the influence of an increased air temperature on the net CO_2 flux, i.e., NEE, is quite site-specific. More observation years are needed to reduce the estimation errors of NEE. Compared with NEE, the N_{neg} at summer midday was relatively stable across different years (Table 2). Hence the measured N_{neg} in the reported year is likely representative of local aerosol production at the site."

Line 400: I don't understand the purpose of Figure 9. The error bars represent different percentiles on the x and y axes, and the meaning of the dots is not explained (are they means? medians?). In addition, I expected the authors to discuss the relationship between NEE and N_{neg}, but this scatter plot does not seem to address that. It is more like putting data together.

Reply: Line 413 for the figure caption is revised "Figure 9. Comparison between the median NEE, median negative intermediate ions at 2.0-2.3 nm, and median air temperature at midday in summer between the sites. The error bars are the 10th and 25th percentiles for NEE, the 75th and 90th percentiles for the negative intermediate ions, and the 75th and 90th percentiles for the air temperature at each site". The Figure 9 has been revised and we now briefly discuss the factors that can cause the observed differences in NEE and N_{neg} across the ecosystems (see reply above). The main scope is to present the potential of different ecosystems influencing the CO_2 uptake and local aerosol production. By clustering similar ecosystems, Figure 9 clearly demonstrates that the differences in NEE and N_{neg} are associated quite strongly with the type of an ecosystem, and not only with meteorological drivers.

The direct connection between NEE and N_{neg} was weak within sites (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 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentile of N_{neg} in each NEE bin were plotted). Explaining the correlation between NEE and N_{neg} is out of scope of the present manuscript and will be investigated in follow-up studies.

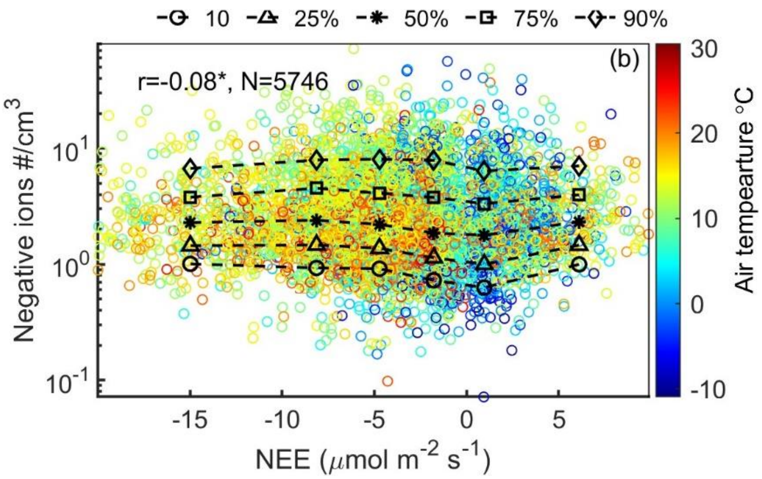

Figure example3. The correlation between NEE and N_{neg} at Hyytiälä forest in summer when PPFD is above 600 μmol m^{-2} s^{-1}. Half-hour mean data are used.

Reference

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