Reviewer #2

I apologise to the editor and to the authors for my delayed response. I read the manuscript titled "Contribution of fine roots on carbon allocation patterns in Norwegian forests" by Hagenbo et al., and I have the following comments and suggestions for improvement. Overall, I find the study to be a valuable contribution to our understanding of fine-root contributions to boreal forest carbon budgets, and I appreciate the authors' comprehensive approach. However, there are some areas where clarification and additional analysis could strengthen the manuscript.

Thank you very much for your valuable input!

Major points

1 - Given the complexity of the methods, I suggest adding a clear diagram (e.g., a flowchart) that maps the different pathways for estimating foliage biomass and fine root production across the three methods. This would help readers grasp the workflow and method-specific differences more quickly. In the same direction, I also suggest restructuring the Methods section to reduce repetition of shared steps and emphasise the differences among the three approaches. For example, the manuscript could include a main workflow subsection for shared components (tree NPP calculation, understory NPP, and GPP/CUE calculation), followed by a separate subsection detailing how foliage biomass and fine root production are estimated in each method. This would reduce redundancy and improve clarity.

We have now included a flowchart illustrating the overall workflow and the main methodological steps. During the development of this figure, we initially attempted to include all the dataset-specific branches; however, this resulted in a figure that was overly complex and difficult to interpret. We therefore present a simplified version focusing on the main analytical steps from start to finish.

Since the flowchart is not space-efficiency we have decided to put this into the Supplementary Information in the manuscript. This is the new figure with its caption. Please note that we have indicated by numbers the section in material and methods that the flowchart refers to:

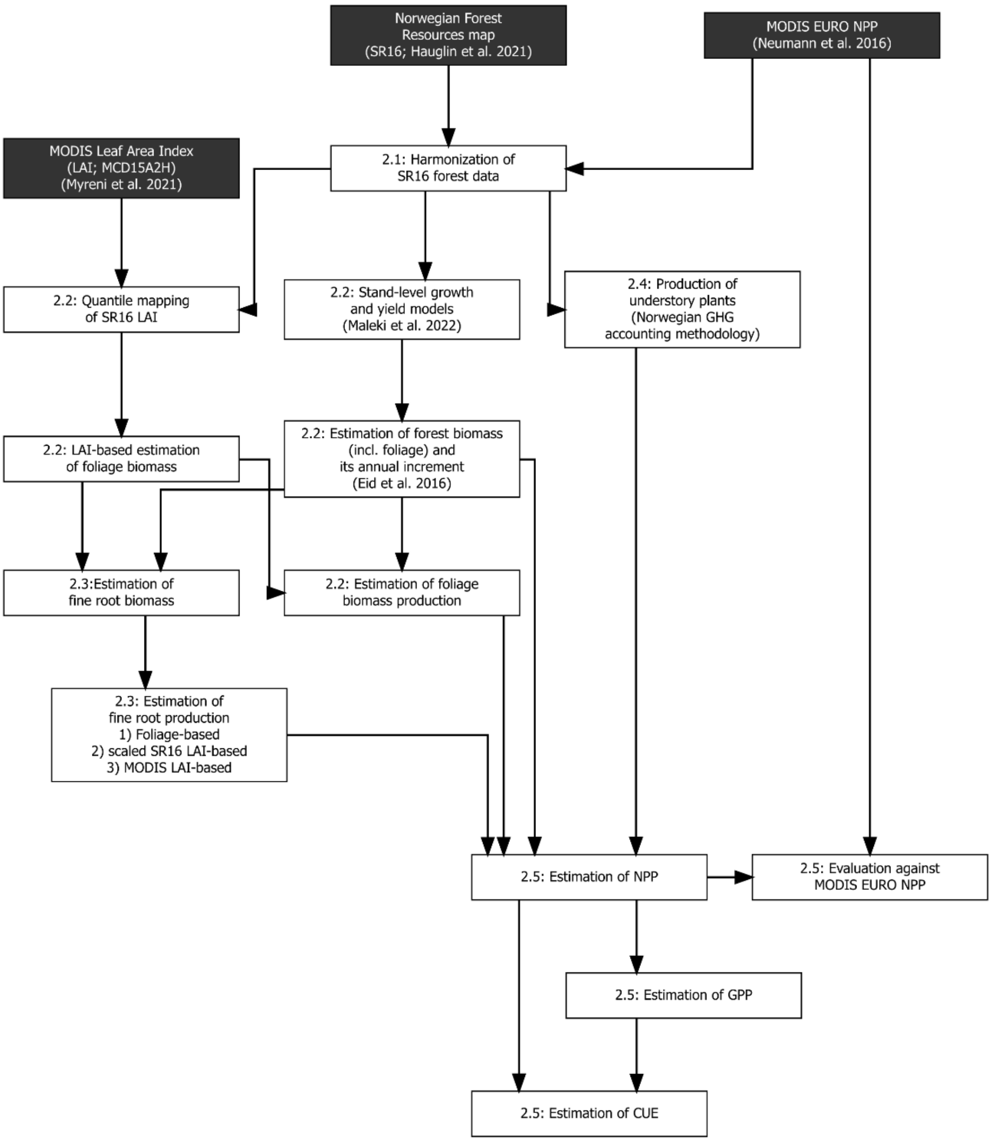

Figure S1: Flowchart of the workflow used to derive estimates of net primary production (NPP), gross primary production (GPP), and carbon use efficiency (CUE) of Norwegian forests. Filled boxes represent the main datasets used in the study, whereas open boxes indicate the different methodological steps. Numbers within the boxes refer to the corresponding sections in the Materials and Methods.

We have also added several clarifications to materials and methods and we think with these changes combined the material and methods section is easier to follow.

2 - Temporal consistency of remote sensing inputs and implications of missing respiration acclimation:

I suggest a dedicated clarification paragraph in Methods (and a short caveat in Discussion) on the temporal representativeness of all remotely sensed/model inputs. As currently described, the workflow appears to combine products from different temporal frames:

- MODIS EURO NPP comes from Neumann et al. (2016), which is a temporally continuous product for 2000-2012.
- MODIS land cover is from MCD12Q1 (2000), and LAI/FPAR is from MOD15 Collection 5.
- SR16 is based on national airborne laser scanning initiated in 2015.

This suggests the analysis is primarily a cross-sectional/fused estimate rather than a strictly year-specific carbon budget. Please state explicitly whether outputs should be interpreted as: (i) representative of a specific year, (ii) a multi-year climatological synthesis, or (iii) a structural comparison among methods independent of a single target year.

Yes, this is an important detail and we now more explicitly highlight the different temporal extents of the datasets in the methods section. However, my co-author pointed out that we align the MODIS LAI and MODIS Euro NPP better than previously described, which was incorrect,. Now we write, at line 144 -149:

> *"To explore and compare both approaches, we used the foliage biomass estimates from the models of Eid et al. (2016) and LAI from MODIS and from SR16, the latter derived from NFI data for 2007–2015 (Majasalmi et al. 2018). LAI from MODIS was obtained from the MCD15A2H 8-day product (Myneni et al., 2021), which was the most recent operational MODIS (combined Aqua + Terra) LAI product available at the time of analysis. We used high-quality observations from the full record overlapping with the MODIS Euro NPP dataset (i.e. 2003–2012)."*

Moreover, our analysis should be viewed as a "structural comparison" between methods and we now clarify this in the methodological considering section, in the discussion. In that section we also address the implication of the different temporal extents. Line 556 -565:

> *"A further limitation is that the datasets used in this study are not temporally aligned. The MODIS Euro NPP data used in this study cover the period 2003–2012 and are therefore temporally aligned with the MODIS LAI (MCD15A2H) data, which were derived from observations over 2003–2013 and averaged to produce a single representative estimate. However, the SR16 forest structure data and associated LAI are based on airborne laser scanning campaigns initiated from 2009 onwards, resulting in a temporal discrepancy between the remote sensing and forest inventory datasets. Consequently, the analysis combines information from different time periods and should be interpreted as a structural comparison among alternative approaches to estimating forest C fluxes, rather than as a temporally explicit C budget for a specific year. Despite this temporal mismatch, the similarity between results derived from the two LAI-based approaches (MODIS and SR16) suggests that its influence is limited relative to the differences between the LAI modelling approaches, likely stemming from the quantile mapping applied to align the SR16 LAI distribution with that of MODIS."*

Respiration acclimation concern:

The GPP framework uses fixed/instantaneous temperature responses (e.g., Q10 = 2 for live wood and fine roots; foliage Q10 from the Tjoelker et al. equation), but does not appear to include explicit longer-term thermal acclimation of respiration parameters. In a rapidly warming high-latitude system, this could bias respiration upward relative to acclimated responses. The literature indicates that acclimation can dampen expected increases in respiration under warming, including in boreal/temperate trees (Reich et al., 2016; Huntingford et al., 2017; Zhang et al., 2025). Some potential implications for this study are: Maintenance respiration (Rm) may be overestimated under warmer conditions. Because GPP is computed as NPP + respiration terms, GPP may be biased high if Rm is biased high. CUE (NPP/GPP) may therefore be biased low, especially in warmer subsets and potentially in age/species groups that differ in temperature regime. Apparent age/species gradients in CUE and inferred fine-root allocation fractions may partly reflect differences in respiration parameterisation rather than solely biological allocation differences.

Suggested improvement:

- Add a sensitivity analysis with an acclimated respiration scenario (for example, temperature-dependent downregulation of reference respiration and/or acclimated Q10) and compare impacts on GPP, CUE, and fine-root C allocation.
- At minimum, quantify likely bias direction and uncertainty range introduced by non-acclimating respiration assumptions.

Thank you for raising this point. We acknowledge that plant respiration may change under a changing climate. This is related to the temperature sensitivity of respiration, which is represented in both the MODIS algorithm and our analyses. However, as you note, studies show that this temperature sensitivity itself may adjust through thermal acclimation, thereby dampening the increase in respiration expected under warming. For example, Reich et al. (2016) reported only an approximately 5% increase in respiration under a 3.4 °C warming, compared to an expected ~23% increase without acclimation.

In the present study, however, our objective was not to assess climate or warming effects, but to evaluate how different representations of foliage biomass and fine root production influence estimates of NPP, GPP, and CUE. In short, the analysis is focused on a quantitative assessment of how alternative fine root methodologies affect regional estimates of NPP, GPP, and CUE, rather than on the climate sensitivity of forests.

Incorporating acclimation would require additional assumptions about the magnitude and functional form of temperature adjustment. We recognize that there is a rather large body of work on the parameterisation and constraining of acclimation responses, before for such analyses are warranted for out tree species and Norwegian forests. While studies such as Reich et al. provide a useful starting point for modelling acclimation effects, we are also concerned about translating species-level acclimation responses (derived from individual trees) to stand and MODIS pixel scales. Because the focus of our study is not on the climate sensitivity of forests, and concerns regarding our options for robust parameterisation of respiration acclimation response, we decided to retain the standard Q10-based approach, without acclimation to to maintain consistency with the MOD17 framework, and to preserve the main objective of our study rather than shifting the focus towards the impacts of a changing climate.

However, we agree that the analysis you suggest is both relevant and timely. We see clear value in exploring acclimation effects in future work, particularly in the context of climate change impacts on boreal forest carbon dynamics. Based on your comment, we have now added a short text describing this in the Discussion, line 563 -570:

> *"While our analyses integrate data from different time periods, they also do not explicitly represent longer-term temporal responses in respiration. Maintenance respiration was calculated using fixed temperature sensitivities (Q10), consistent with the MOD17 framework. However, experimental evidence suggests that plant respiration can acclimate to sustained warming, reducing its temperature sensitivity over time and thereby dampening the temperature-driven increase in respiration (Reich et al., 2016). Accounting for such acclimation could influence estimates of GPP and CUE and may provide insight into potential responses of forest C cycling to climate warming. However, further empirical work on*

> *respiration acclimation across boreal tree species, and its scaling from individual trees to stand and regional levels, is needed to better constrain and evaluate such approaches."*

3 - In Section 4.4, the discussion about remote-sensing GPP products is somewhat too general. It is correct that many widely used products are linked, directly or indirectly, to model formulations that include respiration and/or NPP closure, but this is not true of all current GPP products. For example, GOSIF-GPP is a SIF-based product derived from OCO-2 solar-induced fluorescence and empirically calibrated against eddy-covariance GPP, rather than being calculated as NPP plus modelled autotrophic respiration (Li & Xiao, 2019). In addition, Wang et al. (2026) proposed GPP-net, a Sentinel-2-based deep-learning framework that estimates GPP from surface reflectance and PAR, trained against flux-tower GPP, and designed to minimise dependence on land-cover parameterisation and coarse meteorological inputs. This distinction matters here because one of the key limitations identified by the authors is the circularity introduced when GPP is reconstructed from NPP and respiration terms using a MOD17-like framework. Using external products such as GOSIF-GPP and GPP-net could therefore substantially simplify the analysis: they allow benchmarking of modelled GPP without explicitly prescribing maintenance respiration and growth respiration in the GPP calculation, reducing dependence on fixed Q10 assumptions and the associated acclimation problem raised above. In that sense, comparison with one or both products would provide a more independent test of whether the reported CUE and age-related patterns are driven by the fine-root/NPP formulation or by the respiration parameterisation used to back-calculate GPP. At the same time, I would not present these products as complete solutions, because they introduce their own uncertainties (for example, SIF-GPP transferability and gap-filling for GOSIF, and model transfer/generalisation uncertainty for data-driven products), and GPP product uncertainty can differ in northern ecosystems (Li & Xiao, 2019; Marsh & Zhang, 2022). Still, I think the manuscript would be stronger if the authors explicitly discuss these alternative GPP product classes and, if feasible, compare their MOD17-like GPP estimates against GOSIF-GPP and/or GPP-net as an additional sensitivity test.

Thank you for raising this point and for highlighting additional GPP products. These approaches are indeed interesting and relevant from the perspective of deriving more independent estimates of CUE and reducing some of the uncertainty propagation associated with MOD17-type frameworks.

In response to Dr. Pucher's previous comment, we have revised this part of the manuscript and removed the wording related to "circularity". Instead, we now focus on the propagation of uncertainty associated with estimating NPP from GPP, or reconstructing GPP from NPP and respiration terms, as done in our framework. We would also like to clarify that our intention was not to critique remote-sensing GPP products in general, but rather to highlight methodological limitations associated with MOD17-like approaches, including our own implementation. We acknowledge that the GPP products you mention could provide more independent estimates of GPP, and consequently CUE,

In addition to these approaches having their own uncertainties, we recognise that they also have some limitations within the scope of our study. Regarding GOSIF-GPP, it has a resolution about 5.6 km, which mean that we would further aggregate the SR16 data in our analyses, which would result in increasingly more forest stand structure variation being collapsed, making data inference more challenging. Regarding, the GPP-net model, we think this model is very interesting because of its relatively simple input requirements. Being based on Sentinel-2 data it should also be able to provide fine resolution GPP estimates, relevant for this type of our analysis. However, to the best of our understanding, GPP-net is not yet publicly available and still requires further development, as also noted by Wang et al. (2026). We therefore consider such approaches highly relevant for future analyses.

The primary objective of this study was to evaluate how alternative representations of foliage biomass and fine root production influence estimates of NPP, GPP, and CUE, rather than to derive independent CUE estimates from various GPP products. This required a consistent framework in which respiration and belowground carbon allocation could be estimated comparably across the different fine-root approaches. In addition, the use of Norwegian SR16 forest data and region-specific biomass parameterisations was essential to better represent Norwegian forest conditions, extending beyond the standard MOD17 procedure.
We therefore retained the MOD17-consistent framework to ensure methodological consistency and to maintain focus on fine-root representation and forest carbon allocation. Nevertheless, we agree that the use of independent GPP products would be an interesting direction, and we now alternative GPP products in the Discussion (Lines 519–527).

> *"Alternative GPP products also exist, including GOSIF-GPP derived from Orbiting Carbon Observatory-2 observations of solar-induced chlorophyll fluorescence (Li and Xiao, 2019), NIRv-GPP based on near-infrared reflectance of vegetation (Badgley et al., 2019), and more recently GPP-net, which is a predictive deep-learning model trained on Sentinel-2 data (Wang et al., 2026). These approaches are less dependent on C-balance closure assumptions and may therefore provide more independent estimates of GPP. Combining such GPP products with MODIS Euro NPP could consequently enable more independent calculations of CUE. However, uncertainty related to transferability and model performance in northern ecosystems remains an important consideration for remote-sensing-based GPP products (Li and Xiao, 2019; Marsh and Zhang, 2022). In the present study, we instead retained a MOD17-consistent framework to enable comparison of respiration and belowground C allocation across the different fine root modelling approaches."*

Minor points

Line 121: I suggest reporting the resolution in arcseconds, which in this case would be 30 arcseconds, right?

Yes, info added.

> "The MODIS EURO data has a pixel size of about 30 x 30 arcseconds (0.0083° × 0.0083°), with a spatial reference system of WGS 1984, and represents the period 2000–2012."

Line 273: There appears to be a semantic inconsistency in the description of the residual sign. The text states that the foliage-based method underestimated production in both pine and deciduous forests, yet the reported median residual for deciduous forests is positive (+65.1). If residuals are defined as the difference between the study estimate and the reference/meta-analysis value, then a positive residual would indicate overestimation rather than underestimation. Please check the wording or the residual sign convention.

You are referring to this part:

> "However, this method underestimated production for pine and deciduous forests, with median residuals of -79.8 and +65.1, respectively."

This is wrong. Deciduous should have a negative sign. Thank you for pointing out this error. This has been corrected. We also noted that residual of biomass was expressed as a flux (g C m-2 yr-1) in the text above. This has been corrected.