Associate Editor (Patricia Saco) letter

Public justification (visible to the public if the article is accepted and published):
We have now received the comments from two referees, as well as a comment from a member of the hydrologic community and the responses of the authors to all comments. After my own assessment of the manuscript, the comments and the authors' responses, I believe that the manuscript presents a potentially valuable contribution; however, a thorough revision addressing all reviewer comments is necessary before it can be considered for publication. The main points raised by the reviewers are:

1) Questions, methods, and interpretations of results need to be better linked to potential scientific contributions, which should lead to a clearer focus (as stated by both reviewers)
2) An improved description of assumptions and model coupling is necessary to improve clarity (i.e., transfer of fluxes between STEMMUS-SCOPE and Modflow, as requested by rev. 1 and justification use of 1D model as requested by rev.2)
3) A clear rationale for site selection must be provided (both reviewers).
4) The description and justification of calibration procedure must be improved (rev 1).
5) The results section needs to be improved by including a deeper analysis and comparison across sites (both reviewers)
6) The discussion needs to be revised to better highlight scientific interpretation, including in particular the analysis of Temperature results (mentioned by both reviewers)
7) The conclusions could be better linked to the results discussion (rev.1), and recommendations (rev.2). This section will benefit from highlighting the added contribution of this work with respect to previous work.

Beyond these main points, the three set of comments provide constructive and detailed feedback that the authors should carefully address/answer, including comments on how to enhance figures and other useful minor suggestions to enhance readability and flow. I appreciate the authors' thorough responses to all remarks, which is important given that the paper will be returned to the reviewers for further assessment after resubmission.

Dear Dr. Patricia Saco,
We would like to sincerely thank you for giving us the opportunity to revise the manuscript based on the Reviewers comments. The authors have carefully considered all the comments and tried our best to address every one of them. We have restructured the manuscript to clearly emphasize the scientific contributions enabled by the new modelling framework. We hope the revised version meets your expectations and also the execpetations of the Reviewers. Please, have a look at our responses to all comments below.

Sincerely,
Mostafa Gomaa Daoud
On behalf of all co-authors

Authors replay to RC1: 'Comment on egusphere-2025-4179', Emmanuel Dubois, 03 Nov 2025

The reviewer comments are in **Bold black**, while the authors' responses are in **bold blue** text. To avoid repetitions in our replies, we apply order for the comments (1, 2, 3, etc.), to allow for cross-referencing our responses (if needed).

The manuscript "Unravelling groundwater's role in soil-plant-atmosphere continuum: Integrated ecohydrological modelling approach using STEMMUS-SCOPE and MODFLOW 6" presents the development of a coupled soil–plant–atmosphere model linked with a groundwater model to continuously simulate water and energy balances throughout the atmosphere–plant–soil continuum, ultimately aiming to investigate the contribution of groundwater resources to ecosystem dynamics. The topic is timely, promising, and highly relevant to the HESS audience.

Although the subject is compelling and the developed model produces promising results, the manuscript raises several major concerns:

1. **Significant work is needed to realign the research questions, methods, results, and interpretations throughout the manuscript. In its current form, it primarily presents the development of a new (and very interesting) tool and some results, without fully demonstrating its potential or emphasizing its potentially many scientific contributions. Section-specific comments are detailed afterwards.**

Dear Dr. Emmanuel Dubois,
We would like to sincerely thank you for your precious time in reviewing our manuscript and providing valuable comments that led to possible improvements in the current version. The authors have carefully considered the comments and tried our best to address every one of them. We have restructured the manuscript to clearly emphasize the scientific contributions enabled by the new modelling framework. We hope the revised version meets your expectations. Please, have a look at our responses to your comments.

2. **The presentation of the conceptual model raises a fundamental question regarding the representation and exchange of water fluxes between the two models, which could affect the simulated energy budget (see detailed comments).**

Okay, we have answered this in detail in our reply number 15 (see below).

3. **A major methodological limitation that undermines the entire study is the reliance on manual calibration.**

Okay, we have answered this in detail in our reply number 21 (see below).

4. **The results section could be substantially strengthened by exploring the model outputs in greater depth and focusing on the novel insights made possible by the coupling, rather than primarily presenting results that could be achieved with a fully coupled surface–subsurface model.**

Okay, we have answered this in detail in our reply number 22 (see below).

5. **The discussion section currently focuses on linking previously presented results and does not meet the expectations of a scientific discussion in HESS, which should highlight the main contributions of the study and position them within the broader state of knowledge.**

We thank the Reviewer for this constructive comment. To address this, the Discussion section has been significantly expanded and reorganized to better highlight the main contributions of the study and to position the findings within the broader state of knowledge. In particular:

- **We have revised the Discussion sections into 5 sub-sections:**
  - **Soil moisture (Section 4.1.)**
  - **Soil temperature (Section 4.2.), including three separate subsections**
    - **Groundwater temperature and soil temperature (4.2.1.)**
    - **Groundwater level and soil temperature (4.2.2.)**
    - **Groundwater and surface soil temperature and canopy temperature (4.2.3.)**
  - **Evapotranspiration components (Section 4.3.), including three separate subsections**
    - **Subsurface evaporation (4.3.1.)**
    - **Root soil water uptake (4.3.2)**
    - **Root groundwater uptake (4.3.3.)**
  - **Carbon fluxes and SIF (Section 4.4).**
- **Within each Section, we have substantially rewritten the text to better highlight the contribution of the groundwater.**
- **We also added one Figure (Figure 9) in Section 4.2.3**
- **We have also strengthened the discussion with relevant literature and, where appropriate, include comparisons with previous studies in order to place the findings within the broader ecohydrological modelling context.**

Summary and short summary

6. **The abstract is generally well written; however, the study goal (L31-32) is not addressed in the abstract or the manuscript itself. This reflects a broader issue observed throughout the paper. In addition, the main contributions of this work should be more clearly emphasized in the summary.**

Okay, the specific objectives are defined in the manuscript (lines 205-209) and are also added to the abstract (lines 32-35).

Lines 32-35 in revised version:
"This study investigates the groundwater's role in soil-plant-atmosphere processes, in particular, the impacts of groundwater component (mass and energy) on: 1) regulating the soil profile, in terms of moisture and temperature, 2) the dynamics of the unsaturated/saturated zones and its further impact on water fluxes, and 3) the carbon fluxes and vegetation physiological processes (i.e. root water uptake and fluorescence)."

7. **In the short summary, it would also be more appropriate to refer to the types of models used rather than citing their specific names, as this would make the text more accessible to a broader audience.**

Agreed, the short summary is rephrased (lines 59-63).

Lines 59-63 in revised version:
"Groundwater is ignored in soil-plant-atmosphere continuum (SPAC) models, potentially underestimating its impact on soil and vegetation simulation. To address this, an integrated ecohydrological model is developed by coupling a SPAC model to a hydrological model. The coupled model improved simulation of soil moisture, temperature, evapotranspiration, carbon fluxes and fluorescence. The findings highlight groundwater role in ecosystem dynamics and advance water, energy and carbon cycle modelling."

Introduction

8. **The introduction is too long and difficult to follow, as its logical flow requires significant improvement. Rewriting it would help provide a clearer identification of the research gap and the goal of the study. Some comments that could assist in reworking it are provided below.**

Okay, the description of the two models is moved to Methods (Lines 240-258) to shorten the introduction.

9. **The first paragraph (L56-73) of the introduction is somewhat dangling. It begins with a discussion of the water, energy, and carbon cycles in ecosystems, then moves to essential climate variables and recent efforts to incorporate new variables to better characterize ecosystems, yet without establishing a clear connection between these ideas. The paragraph ends abruptly, without synthesizing its points or explaining their relevance to the present study.**

Okay, the emphasize of the essential climate variables is removed, and this paragraph is rephrased. In the revised version, we only give examples of the variables (in particular, the vegetation and soil variables) that are widely used to monitor and evaluate ecosystem functioning (Lines 77-85).

Lines 77-85 in revised version:
"To access and monitor ecosystem functioning, a range of different physical variables are recognized (Bojinski et al., 2014; GCOS, 2025). Examples of such variables, in particular the vegetation ones, are: leaf area index, above- and below-ground biomass (Atkins et al., 2018; de Conto et al., 2024), gross primary productivity, net ecosystem exchange, evapotranspiration, plant phenology (Shi et al., 2023) and more recently the sun-induced chlorophyll fluorescence (SIF), which serves as a proxy for tracking the photosynthesis process (Sun et al. 2023). Additionally, other soil-related variables play a significant role in characterizing the ecosystems' functioning, such as soil moisture, surface and subsurface temperature, and evaporation (Bojinski et al., 2014; Zeng et al., 2019; GCOS, 2025)."

10. **The second paragraph (L74-89) provides a relatively good overview of the different soil-plant-atmosphere continuum models but could better articulate why explicitly representing groundwater processes in these models is important. Numerous studies have shown that**

vegetation dynamics cannot be accurately explained without considering groundwater interactions; this point is only introduced later in the third paragraph (L90-106), which is more general in scope and lacks a clear link to the implications for the present study. Similarly, the fifth paragraph (L117-138) returns to the absence of hydrogeological processes in soil-plant-atmosphere continuum models models, but again without a strong connection to the study's objectives.

The introduction was intentionally structured to progressively guide the reader toward the research gap addressed in this study. Specifically, the second paragraph introduces soil–plant–atmosphere continuum (SPAC) models and gives an overview of different SPAC models. The third paragraph then discusses the broader importance of groundwater for ecosystem functioning. The fourth paragraph introduces integrated hydrological models (IHMs), which are widely used to simulate coupled surface and groundwater flow processes. The fifth paragraph returns to the limitations of SPAC models regarding the explicit representation of groundwater dynamics, while the sixth paragraph presents integrated ecohydrological modelling (IEM) frameworks as an approach to combine the strengths of SPAC models and IHMs. Finally, the seventh paragraph defines the research gap and motivates the objectives of this study.

To further clarify the link between the introduction and the objectives:

- **In the revised manuscript, the study objective has been expanded (lines 205-209) and clarified by introducing specific objectives, namely to investigate the impacts of the groundwater component (mass and energy) on: (1) regulating the soil profile in terms of moisture and temperature, (2) the dynamics of the unsaturated and saturated zones and their influence on water fluxes and root water uptake, and (3) carbon fluxes and vegetation physiological processes (e.g., root water uptake and fluorescence). The information presented in the introduction paragraphs is intended to lead logically toward these objectives.**
- **The Discussion section is revised and extended with greater details to explain how the modelling results address and achieve the study objectives (as explained in our reply to major comment 5).**

11. **In the fifth paragraph (L139-162), the inclusion of a table is interesting, but it would fit more appropriately in the discussion section, where the contributions of the model developed in this study could be compared to previous work. In the introduction, it would be more effective to summarize the main limitations of existing integrated ecohydrological models to clearly highlight the knowledge gap that this study seeks to address.**

We agreed that Table 1 could be placed in the Discussion. However, we respectfully prefer to keep Table 1 in the Introduction because: a) the table summarizes the capabilities of the existing integrated ecohydrological models (IEMs), in terms of simulating water cycle process, heat transfer, carbon cycle, physiological processes (e.g. root water uptake and fluorescence) and groundwater processes, based on information already reported from literature, and b) summarizing the limitations of the available IEMs in Table 1 explicitly motivate the research gap, as none of the available IEMs include simulation of groundwater heat processes and SIF (as stated in lines 186-188). The table, therefore, functions as a structured argument leading to our research

objective (which was extended by adding specific objectives in lines 205-209) rather than as a post hoc comparison of the models.

12. **Table 1: It would be useful to include information on whether each model offers an option for automatic calibration, as this would strengthen the comparative value of the table.**

We agreed that automatic calibration is fundamental in modelling (as explained in detail in our reply number 21). However, we respectfully prefer not to add this information to Table 1 as it does not fit the content of Table 1, which focuses primarily on the processes that can be simulated by each model. However, we have added text about automatic calibration in the Discussion/Recommendation section (Lines 1092-1096) to highlight its importance.

13. **L165-167: The model's goal seems overly broad, as it could apply to any integrated ecohydrological model. It would be helpful to specify more precisely what distinguishes this model or what particular integration it aims to achieve.**

Okay, specific objectives are added (Lines 205-209) to highlight the specific aims of the study.

Lines 203-209 in revised version:
"This study aims to investigate the role of groundwater in the soil-plant-atmosphere continuum with a focus on assessing the benefits of explicitly incorporating the groundwater component in modelling soil-plant-atmosphere processes. In particular, the specific objectives are to investigate the impacts of the groundwater component (mass and energy) on: 1) regulating the soil profile, in terms of moisture and temperature, 2) the dynamics of the unsaturated/saturated zones and its further impact on water fluxes, and 3) the carbon fluxes and vegetation physiological processes (i.e. root water uptake and fluorescence)."

14. **Paragraphs L173-184 and L185-192: These paragraphs appear more appropriate for the methods section. A brief sentence in the introduction would be enough to mention both models, especially since they are already referred to earlier in the text.**

Agreed, moved to Methods (Lines 240-258).

Method section

Figure 1 and subsection 2.1

15. **Although the STEMMUS-SCOPE model explicitly accounts for root groundwater uptake, this variable is not directly transferred to Modflow. Instead, it is combined with unsaturated zone water fluxes to calculate the net groundwater recharge, which is the variable passed to Modflow. What is the advantage of grouping these two fluxes together, when they can occur at different time scales and result from independent processes? In dry periods or arid environments, when recharge is null and vegetation depends mainly on groundwater, does this mean that the recharge passed to Modflow becomes negative? How is this handled in the model? Is there a risk of misrepresenting key processes by coupling and simplifying the exchanges between models, especially when moving to 3D modelling? The question of**

groundwater uptake and its feedback on groundwater levels remains largely unresolved, and it would be unfortunate for a new tool such as the one developed in this study to be unable to characterize it in detail. Furthermore, could this approach bias the energy module of the coupling, since the volume of recharge influencing groundwater temperature in the model would differ from the actual recharge volume? While grouping recharge and vegetation groundwater uptake fluxes might be acceptable from a quantitative standpoint, given that they are opposite fluxes, it does not seem valid from an energy standpoint, as their respective impacts are not cumulative.

We thank the Reviewer for this constructive comment. Below, we address each aspect of the question in detail:

Why are fluxes grouped into net recharge?

This is a fair question. For the currently explored coupling, we are quantitatively assessing/evaluating the benefits of coupling STEMMUS-SCOPE with MODFLOW for providing a flexible, process-based representation of water and energy fluxes across different landscapes (starting with 3 sites in the Netherlands). We agree that recharge and ET can occur at different time scales, and further work is needed to explore an integration of the two codes when they may operate at different time scales. For the current effort, however, we believe that running the models at a 30-min time step and passing a net recharge to MODFLOW is adequate for the three investigated sites.

The decision to combine the STEMMUS-SCOPE fluxes (e.g. recharge ($\mathrm{R_g}$), capillary rise (Cap), and groundwater root uptake ($\mathrm{RWU_g}$) into a single net recharge flux passed to MODFLOW 6 is primarily dictated by the structural formulation of MODFLOW 6's boundary condition packages, not by a conceptual choice to simplify or aggregate processes.

- **In standard MODFLOW 6 simulations, recharge and root water uptake can be represented using one of two approaches.**
    - **Historically, MODFLOW users could activate the Recharge (RCH) Package to specify the recharge rates as inputs and also activate the Evapotranspiration Package (EVT) to simulate evapotranspiration removed from the saturated zone. In this approach, the RCH and EVT Packages operate independently; however, the RCH and EVT boundary condition fluxes accounted for internally by MODFLOW 6, such that the final calculated water table level reflects their combined effect on the groundwater system. At the end of the time step, both positive downward ($\mathrm{R_g}$) and negative upward (ET) are grouped to form the net groundwater recharge that actually enters or leaves the saturated zone.**
    - **A second option is to use the Unsaturated Zone (UZF) Package (a more physically-based option) instead of the RCH and EVT Packages. The UZF Package simulates infiltration, runoff, changes in unsaturated zone water content, ET from the unsaturated and saturated zone, and recharge. After the UZF statisfies potential evapotranspiration from both unsaturated and saturead zones, a recharge value is calculated and based on**

such value (whether positive or negative), it affects the groundwater levels (whether rise or drop consequently).

- In the STEMMUS-SCOPE-MODFLOW coupling, we replaced the MODFLOW options (RCH/EVT or UZF) with STEMMUS-SCOPE, since it provides a more detailed and physically-based representation of:
    - Evapotranspiration driven by an energy balance module and detailed plant physiology,
    - Root water uptake that includes both soil water root uptake and groundwater root uptake, and
    - Calculates variably saturated flow through the unsaturated zone flow using Richards' equation with two phased flow that considers rechagre, capillary rise, and subsurface evaporation.
- Within the STEMMUS-SCOPE-MODFLOW coupling, the RCH package is active within MODFLOW. The RCH package is a specified flux boundary that facilitates specification of the net recharge flux (whether negative or positive). By design, the RCH package does not distinguish between different fluxes (in our case: $\mathbf{R_g}$, $\mathbf{Cap}$ and $\mathbf{RWU_g}$) which together form the net recharge flux. This approach preserves mass balance exactly: the net volume of water entering or leaving the saturated zone in MODFLOW 6 equals the net vertical flux computed by STEMMUS-SCOPE at the water table interface. Consequently, the volume of the recharge influencing groundwater temperature is the net recharge flux, which is the actual recharge volume.

Regarding the negative net recharge and the impact on water table:

- In dry periods or arid environments, when the combined upward fluxes ($\mathbf{Cap} + \mathbf{RWU_g}$) exceed downward recharge ($\mathbf{R_g}$), the net flux becomes negative. MODFLOW 6 handles this correctly since the specified flux will be negative. The MODFLOW water budget lists the recharge as an "outflow" in this case, and groundwater levels decline in response, consistent with physical expectations. Thus, even though we do not pass $\mathbf{RWU_g}$ as a separate flux, its effect on groundwater levels is fully represented through its contribution to the net flux. The feedback from vegetation water use to groundwater depletion is therefore captured in the coupled simulation.

Regarding the energy balance:

- The temperature ($\mathbf{R_{Tg}}$) that is passed from STEMMUS-SCOPE to MODFLOW 6 as recharge temperature represents the temperature of the net recharge flux (the summation of $\mathbf{R_g}$, $\mathbf{Cap}$ and $\mathbf{RWU_g}$) and not only the $\mathbf{R_g}$. To clarify that, we clarify that this symbol ($\mathbf{R_{Tg}}$) is the net groundwater recharge temperature in the manuscript (line 281).
- Additionally, the heat flux above the water table ($\mathbf{Q_{heat}}$) calculated by STEMMUS-SCOPE is also passed to MODFLOW 6 as a top boundary of the groundwater energy module in MODFLOW 6. So, the effects of the energy transfer in the unsaturated zone, represented by $\mathbf{Q_{heat}}$ is passed to the saturated zone (in MODFLOW 6) and consequently will impact the groundwater temperature simulation.

Implications when moving to 3D modelling

- **The coupling strategy is conservative and scale-consistent. In 3D applications, the MODFLOW 6 model will be discretized into multiple connected cells in the horizontal direction, while each cell will be connected to one STEMMUS-SCOPE profile in the vertical direction. At each time step, each grid cell will receive a) the vertical fluxes (summation of R_g, Cap and RWU_g for flow and Q_{heat} for energy), and b) the lateral groundwater fluxes (flow and energy) from the horizontally connected cells (calculated by MODFLOW 6 based on head and temperature gradients, respectively). MODFLOW 6 then solves the 3D groundwater flow and energy equations (considering mass balance conservation) with accounting for all vertical and lateral inputs and outputs, respecting the fluxes' magnitude and directions. After solving, MODFLOW 6 returns the updated groundwater level and groundwater temperature, which will be passed to STEMMUS-SCOPE for the next time step. Therefore, our coupling approach introduces no structural simplifications when moving from 1D to 3D.**

Finally, we emphasize that the two models are coupled and executed at a fine temporal resolution (i.e. 30 mins time steps). This high frequency ensures that different independent processes (R_g, Cap, RWU_g, Q_{heat}) are resolved and their effects on related variables (e.g. groundwater level and groundwater temperature) are preserved. Overall, the aggregation into net recharge occurs after all component fluxes have been simulated by STEMMUS-SCOPE for the current time step. Thus, no information about the relative magnitudes of R_g, Cap, and RWU_g is lost — these are tracked internally in STEMMUS-SCOPE and available for output and analysis. Only the information passed to MODFLOW 6 is aggregated, which is sufficient for MODFLOW 6 to correctly update groundwater level and groundwater temperature given its package formulations.

Subsection 2.2, figure 2

16. **It appears that groundwater levels were measured only at the forested site, while no observation wells are reported at the meadow sites (Cabauw and VeenKampen). How, then, were groundwater levels determined at these sites? It would be useful to clarify this point in the text (L340-343 p.17).**

We apologize for the lack of clarity. All three sites have groundwater level observations. The only difference is that the groundwater observations used in the forested site (Loobos) are not exactly located in the same location as other measurements (including soil moisture, temperature and ET observations), but were retrieved from the nearest observation point (around 500 m away, as shown in Figure 2). While in Cabauw and Veenkampen, the groundwater observations are in the same location as other measurements. To clarify:

- **We have updated Figure 2 with showing the location of the groundwater observations at Veenkampen and Cabauw.**
- **We rephrased the relevant text in lines 445-449.**

Lines 445-449 in revised version:
"GWL was available at Cabauw and Veenkampen from observation wells located close to the main measurement infrastructure (i.e. Eddy Covariance tower) (Fig. 2). While at Loobos, GWL was not available exactly within the site, but obtained from the nearest available observation point

(approximately 500 m away; Fig. 2) via the Data and Information of the Dutch Subsurface (DINOloket) dataset (GDN 2024)."

17. **It would also be important to briefly summarize the type of evapotranspiration data used, since it is later mentioned as a calibration variable. Is this evapotranspiration calculated using the Penman-Monteith method? If so, it represents potential evapotranspiration, and the authors should justify why it can be considered representative of actual evapotranspiration at the sites. If, instead it is based on in-situ measurements, the measurement technique should be clearly specified.**

We apologize for the lack of clarity. The evapotranspiration data is in-situ measurements from Eddy covariance towers at each site. This information is added in lines 442-443.

Lines 442-443 in revised version:
"The ET observations were derived from eddy covariance towers at the three sites, representing actual ET."

18. **More broadly, this raises questions about the motivation behind the selection of these sites, which appear to be pre-existing experimental locations. A short summary of previous research conducted at these sites would help readers better understand the overall context of the study.**

Okay, we have added details about the motivation behind the selection of these sites (lines 400-408).

Lines 400-408 in revised version:
"Those three sites were selected because: a) they provide comprehensive in-situ measurements spanning over the water, energy, and carbon cycles, including meteorological forcing, different observations such as soil moisture and temperature profiles, Eddy covariance flux measurements (e.g. ET, GPP, and NEE), groundwater levels and temperature, and vegetation characteristics (e.g. SIF). Such data density is essential for rigorously testing the hypothesis of this study and evaluating the developed coupled soil–plant–atmosphere–groundwater modelling framework, and b) the sites represent two dominant Dutch landscapes (forest on sandy soil; meadow on clay/peat), allowing preliminary assessment of model transferability across ecosystem types."

Regarding the suggestion to include a short summary of previous research conducted at these sites, we respectfully prefer not to add an extended overview of prior studies to avoid substantial expanding of the manuscript (especially after the revised Discussion) and shifting the focus away from the methodological contribution of the present work. Instead, we ensure that appropriate references to key site descriptions and datasets are provided, allowing interested readers to consult the broader body of literature if needed.

Table 2

19. **The MAQ dataset is not explicitly introduced earlier in the text. Providing a short presentation of it, either in the main text or at least in the table caption, would improve clarity. Based on**

the text (L355-356 p.18), it appears that groundwater levels were only partially available at one site, while Table 2 presents three different datasets for the sites. This should be made consistent.

Okay, we have a short presentation of the MAQ and also the Cesaer datasets in lines 428-434.

Lines 428-434 in revised version:
"The Meteorology and Air Quality (MAQ) dataset is an open-access collection of harmonized meteorological data, Eddy Covariance fluxes, and soil observations for the Loobos and Veenkampen sites, maintained by Wageningen University (van der Molen et al., 2024; 2025; Heusinkveld et al., 2024; Hong et al., 2025). Similarly, the Cesar dataset, operated by the Royal Netherlands Meteorological Institute (KNMI), provides a wide suite of measurements including remote sensing, Eddy Covariance, surface, soil and hydrological measurements in the Cabauw site (Bosveld, 2020; KNMI, 2024)."

For the groundwater levels, we apologize for the lack of clarity. We have rephrased the relevant text as explained in our reply number 16.

20. **It would also be helpful to include the discretization of the model layers (L372-382 p.20) in Table 2. Doing so would make it easier to compare the sites and would improve the readability of the text.**

Okay, we have added a new table (Table 2 in the revised version, line 425) that summarizes the sites characteristics and discretization of the model layers. We kept the content of Table 2 for data sources only.

Subsection 2.3.3

21. **It is somewhat disappointing to read that calibration was performed manually. Calibration represents a major step in both the modeling process and model development. A model that lacks an automatic calibration option is considerably less appealing for reuse, and the absence of automatic calibration results here greatly limits the scope of the study. This is particularly regrettable given that sufficient datasets are available to enable a multi-objective automatic calibration. I strongly recommend implementing such a procedure, as it would increase confidence in the subsequent results and enhance the credibility and applicability of the model. Since other coupled models of this kind already exist (Table 1), including an automatic calibration process would clearly strengthen the contribution of this work and highlight its potential for broader use.**

We thank the Reviewer for this constructive comment. We fully acknowledge that automatic calibration would clearly enhance the confidence of the results and reduce the uncertainties associated with manual calibration.

However, the main aim of this study was to highlight the benefits of adding the groundwater component in modelling soil-plant-atmosphere processes using a new coupling framework

between STEMMUS-SCOPE and MODFLOW 6 models. Establishing the coupling framework was extensively time and effort demanding for the first author to:

a) **Adapt the STEMMUS-SCOPE code to dynamically account for the groundwater variables (e.g. bottom boundary conditions, calculations of recharge and groundwater root uptake fluxes, as explained in Methods)**
b) **Couple the two models using the Basic Modelling Interface (BMI) protocol. This was accompanied by lots of testing to validate the exchange of the variables between the two models and increase the model's credibility.**

Extensive testing was performed to ensure mass conservation and numerical consistency of the exchanged variables, which was essential to guarantee model credibility. Implementing a fully multi-objective automatic calibration within this newly developed coupling framework would require additional methodological development and computational effort beyond the scope of the present proof-of-concept study.

We also apologize for the lack of clarity about the applicability of an automatic calibration option. In principle, the STEMMUS-SCOPE-MODFLOW 6 can be run through an automatic calibration framework such as the Parameter estimation and uncertainty analysis (PEST++) software. The motivation behind selecting PEST++ is that:

a) **Both STEMMUS-SCOPE and MODFLOW 6 models are compatible with PESE++ requirements, without a need to adjust the structure of the models.**
b) **PEST++ has been used before by the first author in conjunction with MODFLOW 6 (Daoud et al. 2024), confirming its technical feasibility.**

In conclusion, we respectfully maintain the manual calibration in this study, as it was designed as a hypothesis driven proof-of-concept investigation focused on evaluating the structural impact of the groundwater on soil-plant-atmosphere dynamics. Nevertheless, we acknowledge the importance of automatic multi-objective calibration and have explicitly incorporated this as a priority direction for future 2D/3D developments in the revised Discussion/Recommendation section.

Lines 1092-1097 in revised version:
"Furthermore, although calibration was performed manually in this proof-of-concept study, future work should incorporate a multi-objective automatic calibration framework to systematically reduce parameter uncertainty and enhance model robustness. Implementing such an approach in future 2D/3D applications will increase confidence in predictive simulations and strengthen the broader applicability of the developed IEM."

Section 3

22. **Presenting the results by site makes the section excessively long (subsections 3.1 to 3.3; p.22-32) and prevents any meaningful comparison between the three sites. It would be much clearer if the results were organized thematically—for example, by calibration results, plant processes, unsaturated zone, and saturated zone. Restructuring Section 3 in this way would**

likely allow for a deeper analysis of the simulation outcomes and better highlight the value of the proposed model coupling. It would be surprising if differences in model performance were not observed across the sites, given variations in calibration and validation data, dominant land cover, and hydrogeological context. Are there any patterns/trends in the input or calibration datasets that were successfully reproduced in the simulations? The exploration of dynamics during dry periods is particularly promising and could be developed further. How did the model represent the effects of drier conditions on vegetation? How were energy and water fluxes influenced within the atmosphere–plant–soil–groundwater continuum? What were the corresponding impacts on groundwater temperature, and how long did these effects persist? Including details on wet periods could also reveal interesting complementary insights.

We thank the Reviewer for this constructive suggestion. We have restructured the Results section (lines 540-733) completely based on themes (as below) rather than study sites. The new themes are:

1) **Overall models performance**
2) **Saturated zone dynamics**
3) **Unsaturated zone dynamics (soil moisture and soil temperature)**
4) **Evapotranspiration**
5) **Carbon fluxes and SIF**

Additionally, Results tables (Tables 5 and 6 in the revised version) were supported by additional information (i.e. differences in KGE and RMSE values) to help for quick and easier comparisons and reduce the corresponding text.

23. **This section reads as relatively superficial in comparison to the potential of the results and would definitely gain from a major restructuring and re-organizing.**

Agreed, the Results section is restructured as explained in our reply to comment number 22.

24. **For all figures in section 3: the use of red and green lines might make them difficult to interpret for color-blind readers.**

Agreed, we have revised all figures to use colorblind-accessible colors (orange and blue).

Section 4

25. **The first two paragraphs of Section 4 (L570-588; p.32-33) read as a summary of the methods and results rather than as part of the discussion. They could be rephrased and more appropriately integrated into the recommendations subsection where they could emphasize the methodological innovations developed in this study.**

Okay, the first two paragraphs are removed and replaced with a short paragraph (lines 810-814) describing the topics of the following subsections.

26. Paragraph L590-611 (p.33-34) is rather long, and its first half reads more like a general explanation of soil moisture dynamics than an interpretation of the study's results. The specific contributions of this work should be clearly highlighted, as they are not currently acknowledged. The same remark applies to the rest of subsection 4.1. If this subsection were renamed "Contributions of the ST-SC-MF6 IEM to the simulation of soil moisture," how would the paragraph be reworked to better emphasize the scientific advances achieved in this study? Comparisons with previous research are also needed: what has been done before, and how does the use of the ST-SC-MF6 IEM generate new insights or improve the representativity of the simulations?

Okay, we have made multiples changes to subsection 4.1. as follows:

- **The original section "Groundwater impacts on the soil profile" has been divided into two separate subsections. In the revised manuscript, subsection 4.1 focuses on groundwater impacts on soil moisture (lines 817-870), while subsection 4.2 addresses groundwater impacts on soil temperature (lines 871-965).**
- **Subsection 4.1 has been substantially rewritten to more clearly emphasize the specific contributions of the ST-SC-MF6 framework to soil moisture simulation. In particular, we now explicitly highlight (i) the role of groundwater in shaping seasonal soil moisture dynamics, and (ii) the contrasting responses across sites with shallow versus relatively moderate groundwater tables.**
- **We have also strengthened the discussion by incorporating relevant literature to support and compare our findings, thereby better positioning the contributions of this study within the existing body of research.**

27. Subsection 4.1 is titled "Effect of groundwater on the soil profile," while 4.2 is titled "Effect of groundwater on water fluxes." However, soil moisture and soil water potential are closely linked to water fluxes in the unsaturated zone. Should these two subsections be merged? It also seems that subsection 4.2 partly repeats the content of 4.1.

Okay, we have made multiple changes to subsection 4.2. (renumbered as Section 4.3 in the revised version) to improve clarity and reduce overlap.

- **The name of this section is changed to "Effect of groundwater on evapotranspiration" with splitting it into:**
  - **4.3.1. Subsurface evaporation**
  - **4.3.2. Root soil water uptake**
  - **4.3.3. Root groundwater uptake**
- **In each subsection, we have substantially rewritten the text to highlight the contribution of the groundwater in each of these evapotranspiration components.**
- **We strengthened the discussion with relevant literature and, where appropriate, with comparisons with previous studies.**
- **To avoid repetitions, we retained only the essential information of the soil moisture and soil potential processes that are already discussed in detail in Section 4.1.**

28. L644-658: what does the "enhancement" of flux simulation refer to (L647, L653)? Is it an increase of simulation quality? Is it the characterization of the contribution of a source to a flux?

We apologize for lack of clarity. The term "enhancement" was intended to refer to an increase in the magnitude of the simulated flux, rather than an improvement in model performance. To avoid confusion. To clarify, we have replaced "enhancement" with "increase" in the revised manuscript at lines 998-999.

Lines 998-999 in revised version:
"At Cabuaw and Veenkampen, RWU_s, which is based on $\psi_{s,i}$ (Eq. 5), was increased by 29.6 and 35.9% respectively."

29. L644-658: what does the "enhancement" of flux simulation refer to (L647, L653)? Does it mean an improvement in the quality of the simulation? or a characterization of the contributions of different sources to the simulated fluxes?

Same as in our reply to comment 28, we have replaced "enhancement" with "increase" in the revised manuscript at lines 983-984.

Lines 983-984 in revised version:
"At Cabauw and Veenkampen, the simulated E_{ss} by ST-SC-MF6 models were increased by 7.3 and 12.6%, respectively, as compared to the ST-SC models."

30. Subsections 4.1 and 4.2 require significant revisions, as they do not clearly identify the main contributions of the study. Instead, they read as dense descriptions linking simulation results together without sufficient interpretation. These sections would become much clearer if the results were presented earlier in a more structured way that guides readers toward the key insights. Moreover, it remains unclear from these two discussion subsections what specific advantages the integrated ecohydrological model offers compared with fully coupled groundwater models, which were also designed to represent surface, unsaturated, and saturated water fluxes and might perform equally well for this purpose.

We thank the Reviewer for this constructive and important comment. Sections 4.1 and 4.2 have been substantially revised to better articulate the main scientific contributions of this study.

Regarding Section 4.1., please see our response to comment 26.

Regarding Section 4.2., (renumbered as Section 4.3. in revised version), please see our response to comment 27.

In addition, the Results section has been restructured thematically (see response to comment 22), allowing the Discussion to build more clearly on identified patterns rather than revisiting site-by-site descriptions.

Regarding the comparison with fully coupled groundwater models, we acknowledge that such models can represent surface, unsaturated, and saturated water fluxes. However, the key advantage of the ST-SC-MF6 framework lies in its explicit integration of groundwater dynamics with detailed soil–plant–atmosphere and carbon-energy exchange processes. Unlike traditional fully coupled groundwater models that primarily focus on hydrological fluxes, the ST-SC-MF6 framework enables two-way feedback between groundwater, soil moisture, vegetation physiology, and carbon fluxes (GPP, NEE). This integration allows assessment not only of hydrological states but also of ecosystem functioning and productivity, thereby extending the scope from hydrological to ecohydrological representativity.

31. **Subsection 4.3 presents interesting links and could be expanded further. Could the simulation results be used to quantify the relative proportions of water sources used by plants? This analysis could be added to the results section and discussed here, allowing comparison with plant water source estimations based on isotopic methods. Another avenue worth exploring would be to assess the role of plant water uptake in reducing groundwater recharge or contributing to groundwater level depletion, alongside evaluating the influence of groundwater on sun-induced chlorophyll fluorescence.**

We thank the Reviewer for this constructive comment. We have expanded this subsection and provided additional details (lines 1042-1070) to highlight the contribution of groundwater on carbon fluxes, supported by relevant literature.

Regarding the relative proportions of water sources used by plants:

- **We have provided in detail relevant information in the revised Section 4.3. with its new subsections, as explained in our reply 27.**

Regarding role of plant water uptake in reducing groundwater recharge:

- **We didn't add specific text for that purpose since the revised section (Section 4.3.), that focused on groundwater impact on evapotranspiration components, becomes already long enough. Rather, this aspect was mentioned partially in relevant locations within the revised manuscript. For example:**

Lines 840-843 in the revised manuscript
"Further towards summer periods (July – September), limited or no precipitation reduced the R_g, leading to GWL decline and the development of a drier soil profile (Gao et al., 2017; Li et al., 2017) with minimum θ values of 0.2 m3 m-3 at Cabauw and 0.15 m3 m-3 at Venkampen respectively (Fig. 3)."

Lines 863-866 in the revised manuscript
"Nevertheless, the ST-SC models at the three sites were unable to reproduce the observed amplitude and seasonal θ variability. As the absence of dynamic groundwater feedback prevented realistic representation of key interacting processes, i.e. RWU_s, R_g and their combined influence on θ."

Regarding influence of groundwater on sun-induced chlorophyll fluorescence

- we retained the original text and didn't add further discussion because the available literature directly addressing groundwater – SIF relationship is still very limited. We acknowledge that this is an interesting research direction and consider it a promising topic for future investigation.

32. **Subsection 4.4 largely repeats limitations already discussed elsewhere in the manuscript. Instead, a concise summary of the main contributions of this work would help readers assess the novelty and scientific value of the study, as well as the potential applications of the developed model. A conceptual diagram could also be used to clarify the study's main contributions and illustrate how the model can support other research.**

We thank the reviewer for this suggestion. Section 4.4 (renumbered as Section 4.5 in the revised manuscript) is intended to summarize the limitations of the current study and provide recommendations for future research, rather than to restate the main contributions of the work. For this reason, we retained the structure and focus of this section. The main contributions and novelty of the study are already summarized in the Conclusion section. Nevertheless, we carefully reviewed the section to ensure that it remains concise and avoids unnecessary repetition.

33. **Finally, it is disappointing that the temperature module of the simulations was not further explored or discussed in this section. The introduction emphased on this component and justified the development of a new integrated ecohydrological model partly on that basis. It would therefore be appropriate to examine and discuss this aspect in greater detail here.**

We thank the Reviewer for this constructive and important comment. In response, we have added a new separate Section (Section 4.3.) titled "Effect of groundwater on soil temperature". In this new section, we provide a more detailed analysis of:

- The impact of groundwater temperature on soil temperature (subsection 4.3.1).
- The impact of groundwater level on soil temperature (subsection 4.3.2).
- The impact of groundwater on surface soil temperature and canopy temperature (subsection 4.3.3).

Each subsection includes a comparison between the three sites, highlighting how site-specific groundwater conditions influence the simulated soil thermal processes. In addition, the subsections are strengthened with relevant literature to better place our findings in the context of previous studies.

<u>Conclusion</u>

34. **L703: The term "qualitative" seems inappropriate, as the study does not include any qualitative approaches.**

Okay, removed (line 1129).

35. **The conclusion is too long and overly dense, likely because it attempts to summarize all the study's findings. While some of these findings are indeed interesting, their demonstration is not always clearly supported by the results and discussion sections.**

Agreed, the Conclusion section (lines 1102-1120) has been completely rewritten and shortened to improve clarity and focus. We removed overly detailed statements and ensured that the remaining conclusions are directly supported by the revised Results and Discussion sections. The revised Conclusion now highlights only the main findings of the study and their implications for modelling the soil–plant–atmosphere continuum.

Authors replay to RC2: 'Comment on egusphere-2025-4179', Anonymous Referee, 23 Dec 2025

The reviewer comments are in **Bold black**, while the authors' responses are in **bold blue** text.

Full Title:
Unravelling groundwater's role in soil-plant-atmosphere continuum: Integrated ecohydrological modelling approach using STEMMUS-SCOPE and MODFLOW 6

Overall evaluation:
This study investigates the role of groundwater in the soil-plant-atmosphere continuum by coupling the STEMMUS-SCOPE SPAC model with MODFLOW 6 to simulate key variables such as soil moisture, temperature, groundwater levels, and ecosystem processes at three locations in the Netherlands. While the research addresses an important topic in ecohydrological modeling, there are notable limitations that need addressing：1） although the coupled model aims to improve accuracy in vegetation carbon dynamics through groundwater integration, indicators like GPP show no significant improvement compared to single-model results, raising questions about the necessity of using a coupled approach. 2） the one-dimensional nature of the model limits its ability to capture lateral runoff dynamics, particularly in agricultural landscapes where water level fluctuations are significant. 3） It is important to improve result presentation, as current figures lack clarity. Overall, while the study has potential significance, it requires substantial revisions to address these issues and better communicate findings.

Dear Reviewer,
We would like to sincerely thank you for your precious time in reviewing our manuscript and providing valuable comments that led to possible improvements in the current version. The authors have carefully considered the comments and tried our best to address every one of them. We have restructured the manuscript to clearly emphasize the scientific contributions enabled by the new modelling framework. We hope the revised version meets your expectations. Please, have a look at our responses to your comments.

Major concerns:

1. **It is widely recognized that explicitly representing groundwater mass and energy within an IEM framework improves the quantification of the SPAC. A more carefully formulated hypothesis could better inspire readers.**

Okay, the research hypothesis (lines 193-197) is expanded to state the study's contributions.

Lines 193-197 in revised version:
"The hypothesis of this study is that explicit representation of groundwater mass and energy in an IEM framework would improve quantification of the soil–plant–atmosphere continuum by: a) improving the simulation of soil moisture and temperature profiles, b) enabling two-way feedbacks between the unsaturated and saturated zone and their further impact on water fluxes, and c) revealing the groundwater's influence on carbon fluxes and vegetation physiological processes such as root water uptake and fluorescence. Collectively, testing these hypotheses would unravel

the groundwater role in shaping the SPAC dynamics and deepen the understanding of ecosystem functioning."

2. **Three field sites and corresponding observational data were used to apply and test the coupled model. However, the rationale for selecting these specific sites and the underlying motivations for conducting the modelling work there are not detailed.**

Okay, we have answered this in our reply to the detailed comment number 1.

3. **While the effects of groundwater are noted, the discussion regarding its influence on the soil profile, water, and carbon fluxes could be expanded. Providing specific results and illustrative figures would greatly clarify this crucial aspect, which is fundamental to readers' interpretation of the work.**

We thank the Reviewer for this constructive comment. To address this, the Discussion section has been significantly expanded and reorganized to better highlight the main contributions of the study and to position the findings within the broader state of knowledge. In particular:

- **We have revised the Discussion sections into 5 sub-sections:**
  - **Soil moisture (Section 4.1.)**
  - **Soil temperature (Section 4.2.), including three separate subsections**
    - **Groundwater temperature and soil temperature (4.2.1.)**
    - **Groundwater level and soil temperature (4.2.2.)**
    - **Groundwater and surface soil temperature and canopy temperature (4.2.3.)**
  - **Evapotranspiration components (Section 4.3.), including three separate subsections**
    - **Subsurface evaporation (4.3.1.)**
    - **Root soil water uptake (4.3.2)**
    - **Root groundwater uptake (4.3.3.)**
  - **Carbon fluxes and SIF (Section 4.4).**
- **Within each Section, we have substantially rewritten the text to better highlight the contribution of the groundwater.**
- **We also added one Figure (Figure 9) in Section 4.2.3.**
- **We have also strengthened the discussion with relevant literature and, where appropriate, include comparisons with previous studies in order to place the findings within the broader ecohydrological modelling context.**

4. **The manuscript does not detail how soil heterogeneity in the profiles was addressed in the modelling. Clarifying how this critical factor is accounted for is essential for assessing the model's applicability and accuracy.**

We apologize for the lack of clarity. The soil profile was discretized into a number of several vertical layers at each site. Before the start of the simulations, all layers were assigned uniform values. Then, during the calibration, the soil parameters were updated to reflect the soil heterogeneity and improve the match between observed and simulated values. To clarify:

- **A new table (Table 2 in the revised version) is added that summarizes the sites' characteristics and discretization of the model layers.**
- **The table of the parameters (Table 4 in the revised version) is updated with the ranges of the calibrated values instead of the previous one dominant value.**
- **Relevant text is added in lines 520-525.**

Lines 520-525 in revised version:

"As explained in Section 2.4.1, the soil profiles at each site were discretized into multiple vertical layers (Table 2) to account for soil heterogeneity. Initially, all layers were assigned uniform values for each parameter. During the calibration procedure, these parameters were updated individually for each layer to reflect the vertical variability of the θ and T_s measurements. The ranges of the calibrated values for each parameter across the layers are summarized in Table 4."

5. **The study's primary focus appears ambiguous: is it to present a new modelling framework, or to elucidate the specific role of groundwater within the SPAC system? Clarifying this objective would strengthen the paper's contribution. If the former, the model structure requires a more detailed and systematic introduction. If the latter, the analysis of groundwater's effects should be substantially deepened and discussed with greater insight.**

The study focused on the groundwater contribution to SPAC modelling rather than presenting a new modelling framework. To address this, the Discussion section has been significantly expanded and reorganized to better highlight the main contributions of the study and to position the findings within the broader state of knowledge, as we have explained in detail in our reply to major comment 3.

Detailed comments:

1. **The choice of the three field sites (Loobos, Cabauw, Veenkampen) lacks justification. Merely noting that results differ across sites is insufficient; the significance of these differences for the study's conclusions remains unclear. Explaining why these sites were chosen and what their comparative results demonstrate would greatly enhance the impact of the work.**

Okay, we have added details about the motivation behind the selection of these sites (lines 400-408).

Lines 400-408 in revised version:

"Those three sites were selected because: a) they provide comprehensive in-situ measurements spanning over the water, energy, and carbon cycles, including meteorological forcing, different observations such as soil moisture and temperature profiles, Eddy covariance flux measurements (e.g. ET, GPP, and NEE), groundwater levels and temperature, and vegetation characteristics (e.g. SIF). Such data density is essential for rigorously testing the hypothesis of this study and evaluating the developed coupled soil–plant–atmosphere–groundwater modelling framework, and b) the sites represent two dominant Dutch landscapes (forest on sandy soil; meadow on clay/peat), allowing preliminary assessment of model transferability across ecosystem types."

2. **While it is true that groundwater contributions are inherently variable, presenting this as a key finding is too general. The abstract could be more compelling by specifying how the variability manifests in your study systems (e.g., its primary drivers or magnitude) and what new understanding it provides.**

We thank the Reviewer for this comment. To address this, we have tried to be more specific and highlight the exact groundwater contributions in the abstract. Below is the revised sentence

Lines 49-54 in revised version:

"Notably, benefits of ST-SC-MF6 simulation were particularly prominent during both wet and dry periods, i.e. improving the representation of: a) the θ dynamics during wet conditions, when hydraulic connectivity between the phreatic surface and the unsaturated zone is strong, b) the root water uptake and carbon assimilation during dry periods, when shallow groundwater mitigated vegetative water stress. and c) the T_s dynamics during both wet and dry periods, influenced by both GT and GWL, and further propagated to other T_s dependent processes."

3. **The statement attributes the benefits during dry periods to groundwater mitigating water stress. To substantiate this key conclusion, it is necessary to clarify: how was this causal relationship established? What analysis directly connects the simulated benefits to the reduction of vegetative water stress?**

We thank the Reviewer for this comment. To address this, we have refined one of the Discussion subsections to focus on the groundwater contribution to evapotranspiration components. In subsections 4.3.2. and 4.3.3., we have substantially rewritten the text to highlight the contribution of the groundwater in root soil water uptake (lines 994-1009) and root groundwater uptake (lines 1010-1030) respectively. Additionally, we strengthened the discussion with relevant literature and, where appropriate, with comparisons with previous studies.

4. **Lines 41-42: The performance description here would be more concrete if supported by a specific numerical value, such as a key performance indicator or an error metric.**

Agreed, we have updated the relevant sentence (lines 46-49) with the difference in the KGE values (which was also added to Table 5) between the two setups (with and without groundwater).

Lines 46-49 in revised version:

"The ST-SC-MF6 showed better agreement with observations than the ST-SC, improving the KGE values for: a) T_s (+0.19), and ET (+0.35) at Loobos, b) θ (+0.30), ET (+0.11), NEE (+0.18), and SIF (+0.05) at Cabauw, and c) θ (+0.21), and ET (+0.15) at Veenkampen."

5. **The summary should move beyond stating the known importance of groundwater. Its stronger point is the demonstrated need to include groundwater processes in models, and this focus should be sharpened.**

Okay, the short summary is rephrased to demonstrate the importance of including groundwater in soil-plant-atmosphere continuum models (lines 60-65).

Lines 60-65 in revised version:

"Groundwater is ignored in soil-plant-atmosphere continuum (SPAC) models, potentially underestimating its impact on soil and vegetation simulation. To address this, an integrated ecohydrological model is developed by coupling a SPAC model to a hydrological model. The coupled model improved simulation of soil moisture, temperature, evapotranspiration, carbon fluxes and fluorescence. The findings highlight groundwater role in ecosystem dynamics and advance water, energy and carbon cycle modelling."

6. **The descriptions of the various model types are somewhat repetitive. Condensing this section would improve clarity and focus.**

Okay, the introduction is shortened. The description of the models is moved to Methods (lines 240-258).

7. **Lines 61-62: The jump to ECV indicators here is logically abrupt. Consider combining this sentence with the next and adding a brief transition.**

Okay, the emphasize of the essential climate variables is removed, and this paragraph is rephrased. In the revised version, we only give examples of the variables (in particular, the vegetation and soil variables) that are used to monitor and evaluate ecosystem functioning (Lines 77-85).

Lines 77-85 in revised version:

"To assess and monitor ecosystem functioning, a range of different physical variables are recognized (Bojinski et al., 2014; GCOS, 2025). Examples of such variables, in particular the vegetation ones, are: leaf area index, above- and below-ground biomass (Atkins et al., 2018; de Conto et al., 2024), gross primary productivity, net ecosystem exchange, evapotranspiration, plant phenology (Shi et al., 2023) and more recently the sun-induced chlorophyll fluorescence (SIF), which serves as a proxy for tracking the photosynthesis process (Sun et al., 2023). Additionally, other soil-related variables play a significant role in characterizing the ecosystems' functioning, such as soil moisture, surface and subsurface temperature, and evaporation (Bojinski et al., 2014; Zeng et al., 2019; GCOS, 2025)."

8. **Lines 81-85: Presenting model developments requires more than an isolated list of additions. A concise review of the baseline SPAC model's history and key features is needed to root these advancements in a clear foundation.**

We thank the reviewer for this helpful suggestion. We agree that presenting model developments should not appear as an isolated list of additions without sufficient context. However, our aim is not to present detailed model developments, but rather to highlight the limitations of such SPAC models since SPAC models either ignore or oversimplify the underlying groundwater system as stated in lines 149-170. We then go towards the available IEMs that overcome the SPAC models' limitations and present the capabilities of the available IEMs in Table 1, concluding with the limitations of the available IEMs, as none of the available IEMs includes simulation of groundwater heat processes and SIF (as stated in lines 188-190). The limitation of SPAC models and available IEMs explicitly motivates the research gap, leading to our research objective (which was extended by adding specific objectives in lines 205-209). Therefore, we respectfully prefer not to expand the

text about the developments of the SPAC models and IEMs to avoid substantial expanding of the manuscript and shifting the focus away from the methodological contribution of the present work.

9. **Lines 94-96: The causal claim here is unsupported. An increase in groundwater discharge does not logically equate to being "exposed" to climate change impacts. Please rephrase to accurately describe the relationship.**

Okay, the sentence is rephrased (lines 120-124) to be:
"*Groundwater-dependent ecosystems can be exposed to surface water – groundwater interactions, through altered recharge or discharge rates. Such changes may impair their ecological function if groundwater availability declines, particularly under future climate regimes (Otoo et al., 2025).*"

10. **Lines 100–103: The supporting role of groundwater in vegetation physiology is attributed primarily to its relative hydrological stability, not to a lag phenomenon. The wording should be adjusted to reflect this correct causal mechanism.**

Okay, the sentence is rephrased (lines 128-132) to be:
"*Additionally, groundwater systems typically respond more slowly to meteorological forcing, as compared to the surface water or the near-surface soil moisture, due to their larger storage and longer flow paths. This relative hydrological stability allows groundwater to continue supporting vegetation in mitigating water stress effects during prolonged drought periods after soil moisture has been depleted.*"

11. **Lines 110–111: This sentence appears logically disconnected from both the preceding and following content. Its relevance to the narrative flow should be clarified or it should be rephrased to establish a clearer connection.**

Okay, the sentence is removed.

12. **Lines 157–158: The statement notes that existing models "all lack the representation of groundwater heat processes and groundwater temperature simulation." To strengthen the manuscript, please clarify whether your study addresses these specific gaps. If it does, highlighting this contribution in the abstract would underscore its significance. If not, consider phrasing the limitation in a more measured, forward-looking manner (e.g., "few studies have incorporated…").**

Yes, our manuscript addresses this gap as mentioned in the next lines of the same paragraph (lines 191-193). To clarify this point, we have added it explicitly in the study objectives (lines 205-209) and also in the abstract (lines 32-35).

Lines 191-193 in revised version:
"*Hence, a new IEM is needed that can physically-based integrate the groundwater processes (mass and energy) with detailed energy, carbon and SIF fluxes*"

In addition, we have added a new section in the Discussion (Section 4.2), with three subsections, to highlight:

- The impact of groundwater temperature on soil temperature (subsection 4.2.1).

- **The impact of groundwater level on soil temperature (subsection 4.2.2).**
- **The impact of groundwater on surface soil temperature and canopy temperature (subsection 4.2.3).**

13. **Lines 165–172: This paragraph does not effectively articulate or foreground the key research contributions of this study. It should be revised to clearly underscore the novel points being presented.**

Okay, the research objectives (lines 205-210) are extended to state the novel contributions.

Lines 205-210 in revised version:

"This study aims to investigate the role of groundwater in the soil-plant-atmosphere continuum with a focus on assessing the benefits of explicitly incorporating the groundwater component in modelling soil-plant-atmosphere processes. In particular, the specific objectives are to investigate the impacts of the groundwater component (mass and energy) on: 1) regulating the soil profile, in terms of moisture and temperature, 2) the dynamics of the unsaturated/saturated zones and its further impact on water fluxes, and 3) the carbon fluxes and vegetation physiological processes (i.e. root water uptake and fluorescence)."

14. **Lines 169–170: The parenthetical remark "(which will be extended to 2D/3D in a follow-up study)" pertains to future work rather than the present study's contributions. Unless critical for contextualizing current limitations, it can be removed to maintain focus on the reported research.**

Agreed and removed.

15. **Lines 173–192: This discussion would be more logically positioned within the earlier section that introduces the first two model types, thereby improving the overall structural coherence.**

Okay, the description of the two models is moved to Methods (Lines 237-256) to be positioned immediately before the coupling of the two models (as also suggested by Reviewer 1).

16. **A clear scientific hypothesis is needed in the Introduction to establish focus and testability.**

Okay, the hypothesis is expanded with details (lines 193-197) to align also with the specific objectives (lines 205-209), as also mentioned in our reply to detailed comment 13.

Lines 193-197 in revised version:

"The hypothesis of this study is that explicit representation of groundwater mass and energy in an IEM framework would improve quantification of the soil–plant–atmosphere continuum by: a) improving the simulation of soil moisture and temperature profiles, b) enabling two-way feedbacks between the unsaturated and saturated zone and their further impact on water fluxes, and c) revealing the groundwater's influence on carbon fluxes and vegetation physiological processes such as root water uptake and fluorescence. Collectively, testing these hypotheses would unravel the groundwater role in shaping the SPAC dynamics and deepen the understanding of ecosystem functioning."

17. **Study Sites and Data: The rationale for selecting these three specific locations to apply the model requires a more objective and well-reasoned explanation. Please clarify the scientific basis for their selection (e.g., representing a gradient of key conditions, data availability, or specific hypotheses to be tested) to justify the study design.**

Okay, we have explained the motivations behind the selection of the study sites in our reply to detailed comment 1.

18. **Lines 368–371: The content of this paragraph is more closely aligned with the site or data description. For better organizational flow, it is recommended to relocate it to Section 2.1.**

Okay, we have moved this paragraph to lines 205-212 to be positioned after the study objectives.

Lines 209-218 in revised version:
"To address these objectives, a new IEM framework is developed by coupling the STEMMUS-SCOPE SPAC model to the MODFLOW 6 IHM model and applied to three sites in the Netherlands (i.e., Loobos, Cabauw, and Veenkampen). Since STEMMUS-SCOPE is a point-based model, MODFLOW 6 is a grid-based model, and this study is the first example of coupling these two models, the ST-SC-MF6 models were set up in a vertically-stacked orientation (1-dimensional, 1D). The 1D models were assumed to be representative of the ecosystem of each of the corresponding sites."

19. **Lines 426–427: The criteria for deeming the listed RMSE values as "acceptable" are not self-evident. Please provide a justification or cite relevant references that establish these specific thresholds as benchmarks for model performance acceptance in similar studies. This is essential for assessing the rigor of your model calibration.**

Okay, we have added multiple references which used similar RMSE values (lines 534-539).

Lines 534-539 in revised version:
"The RMSE value was deemed acceptable when it was minimized to 0.1 m^3 m^{-3}, 2°C, 0.5 m, 1°C, 1 mm day^{-1}, 3 gC m^{-2} day^{-1}, 5 gC m^{-2} day^{-1}, and 0.25 mW m^{-2} um^{-1} sr^{-1} for θ, T_S, GWL, GT, ET, GPP, NEE, and SIF, respectively, as similar ranges were indicated in former studies (Lekula & Lubczynski, 2019; Pacheco-Labrador et al., 2019; Thum et al., 2019; Van der Velde et al., 2023; Benz et al., 2024; Qian et al., 2024; Yang & Lei, 2024; Wang et al., 2026)."

20. **The results section contains excessive descriptive text that merely reiterates what is already visible in the figures. To strengthen this section, focus on concisely presenting the key findings and their interpretation, rather than describing the data trends in detail.**

Okay, we have restructured the Results section completely based on themes (as below) rather than study site to focus on key findings and their interpretations and also for easier comparison between the three sites. The new themes are:

6) **Overall model's performance**
7) **Saturated zone dynamics**
8) **Unsaturated zone dynamics (soil moisture and soil temperature)**
9) **Evapotranspiration**

10) Carbon fluxes and SIF

Additionally, Results tables (Tables 5 and 6 in the revised version) were supported by additional information (i.e. differences in KGE and RMSE values) to help for quick and easier comparisons and reduce the corresponding text.

21. **Lines 460-463: The results indicate that the model coupling did not improve the accuracy of GPP simulations. This appears to contradict the central hypothesis regarding groundwater's significant influence on vegetation. Please discuss this discrepancy. Does it suggest the influence is negligible under these conditions, or are there other explanatory factors (e.g., model limitations, data scale)?**

We thank the Reviewer for this comment. We acknowledge that in Loobos, the GPP simulations of both cases (with and without groundwater) aligned well with the observations. However, this was a specific case due to the characteristics of the Loobos site, which has relatively moderate groundwater levels and generally low values of soil moisture (max observed value was 0.16 m^3m^{-3}). However, in Cabauw, we observed a significant improvement in the NEE simulation (where GPP was not available in Cabauw) for the coupled ST-SC-MF6 model than the ST-SC model.

- **To clarify, we have split and expanded the related text in the Discussion into four paragraphs:**
- **Paragraph 1 (lines 1035-1045) describes the physical relationship between groundwater and carbon fluxes.**
- **Paragraph 2 (lines 1046-1060) explains the Cabauw case.**
- **Paragraph 3 (lines 1061-1066) explains the Loobos case.**
- **Paragraph 4 (lines 1067-1074) explains the difference between Cabauw and Loobos.**

Lines 1046-1060 in revised version:
"At Cabauw, where GWL is relatively shallow, exerting strong control on the θ dynamics, the ST-SC-M6 showed improved simulation of both θ and NEE. In particular, the NEE was increased during the dry periods (Figs. 7e and f) due to enhancement in the simulated θ resulting from dynamically updated GWL values. This simulated mechanism aligns with recent findings that groundwater depth is a critical control on ecosystem productivity, with higher carbon assimilation occurring under shallow groundwater conditions (Glanville et al., 2023). Specifically, in meadow ecosystems with shallow GWL, such as in Cabauw, shallow groundwater can enhance net carbon uptake by suppressing soil respiration under near-saturated soil conditions, thereby increasing the net ecosystem carbon sink (Sun et al., 2021). Their analysis, in two meadow sites in the Tibetan Plateau in China, revealed that the influence of high θ, maintained by shallow GWL, played a more significant role in controlling the carbon fluxes rather than low temperature. Moreover, the pronounced improvement of simulated NEE during the dry periods (Figs. 7e and f) is consistent with the evidence that there is a significant positive correlation between groundwater depth and carbon fluxes under certain conditions, i.e. when vegetation activity is minimum (Koirala et al., 2017)."

Lines 1061-1066 in revised version:
"Meanwhile, at the Loobos site, there was negligible GWL effect on the simulated θ and consequently on the simulated GPP (Figs. 7b and c). This is because: a) the simulated GWL was relatively moderate (3 – 5 m), limiting its hydraulic connection to the unsaturated zone, consistent

with the observation that deeper GWL reduces carbon fluxes (Glanville et al., 2023), and b) the maximum observed θ was generally low (0.16 m^3 m^{-3}), indicating low water availability for vegetation and consequently poor carbon assimilation."

22. **Model Applicability Concern: The study sites at Cabauw and Veenkampen are situated in agricultural settings. A key limitation is that the employed 1D model framework cannot account for lateral water fluxes, which are likely significant due to irrigation and pumping practices. Please address the potential impact of this simplification on the results and discuss its validity for these sites.**

We thank the Reviewer for this constructive comment. To address this comment, we have added relevant text in the new Results subsection "3.2. Saturated zone dynamics" (lines 587-593)

Lines 587-593 in revised version:
"Although the lateral groundwater flow was not simulated in the present 1D applications, its potential effect was indirectly accounted for calibrating the ST-SC-MF6 models against the observed GWL. By adjusting aquifer parameters so that simulated GWL closely matched observed ones, the 1D ST-SC-MF6 models implicitly incorporated the net outcome of lateral inflows, drainage, irrigation, and pumping on the GWL dynamics. Nevertheless, incorporating lateral groundwater flow in future 2D/3D applications would likely improve process realism, particularly when assessing groundwater as a managed water resource and its broader role in ecosystem functioning."

23. **The section would benefit from a more substantive and critical analysis. Currently, it tends to restate results rather than interpret their significance. For instance, the claim that comparing ST-SC and ST-SC-MF6 results "highlights the benefits" (Lines 586-588) is vague. The discussion should explicitly articulate what these specific benefits are—quantitative improvements, mechanistic insights gained, or limitations addressed—and explain why they matter in the broader context of SPAC modelling.**

Okay, we have rephrased this sentence (lines 814-815) to:
"The benefits of representing the groundwater in models of soil-plant-atmosphere continuum are described in the following subsections."

In addition, we have significantly expanded the Discussion Section to explain in detail those benefits and the differences across the three sites. The structure of the revised Discussion is explained in our reply to major comment 3.

24. **The discussion appears somewhat isolated from the wider body of literature. To strengthen its scholarly contribution, findings should be actively compared and contrasted with existing studies.**

We thank the Reviewer for this constructive comment. To address this, the Discussion section has been significantly expanded and reorganized to better highlight the main contributions of the study and to position the findings within the broader state of knowledge. The new structure of the revised Discussion is explained in our reply to major comment 3.

25. The current recommendations are overly general. To be more useful, this section should transition from stating ambitions (e.g., expanding to 2D/3D) to providing actionable insights based on this study. Please address: 1) What was the actual simulation quality at the three sites? Under what conditions did the coupled model perform well or poorly? 2)

Section 4.4 (renumbered as Section 4.5 in the revised manuscript) is intended to summarize the limitations of the current study and provide recommendations for future research. We believed that the mentioned recommendations would improve the quality of future simulations based on the experience gained during this work.

To further enhance the actionability of the recommendations, we emphasize the need for a multi-objective automatic calibration framework in future studies to improve the quality of the simulations (lines 1092-1096). Regarding what conditions did the coupled model perform well or poor, this is summarized in the Abstract (lines 49-54), where the improvements achieved at each site for specific variables are briefly reported.

Lines 1092-1096 in revised version:
"Furthermore, although calibration was performed manually in this proof-of-concept study, future work should incorporate a multi-objective automatic calibration framework to systematically reduce parameter uncertainty and enhance model robustness. Implementing such an approach in future 2D/3D applications will increase confidence in predictive simulations and strengthen the broader applicability of the developed IEM."

Lines 49-54 in revised version:
"Notably, benefits of ST-SC-MF6 simulation were particularly prominent during both wet and dry periods, i.e. improving the representation of: a) the θ dynamics during wet conditions, when hydraulic connectivity between the phreatic surface and the unsaturated zone is strong, b) the root water uptake and carbon assimilation during dry periods, when shallow groundwater mitigated vegetative water stress. and c) the T_s dynamics during both wet and dry periods, influenced by both GT and GWL, and further propagated to other T_s dependent processes."

26. Based on your experience, what are the main practical or theoretical constraints (e.g., computational cost, data requirements, specific site conditions) that currently limit the model's application? 3) Is the coupled framework readily operable and transferable to other regions? What are the key prerequisites (data, expertise) and potential pitfalls for potential users?

We thank the Reviewer for this comment.

Regarding the main practical or theoretical constraints

- **Based on our experience, the applicability of the coupled framework depends on site conditions. In particular, the model is most beneficial at sites where there is a hydraulic and/or thermal connection between the groundwater system and the unsaturated zone or land surface. When groundwater is relatively deep (e.g., > 10 m below land surface), the influence of groundwater on soil–plant–atmosphere processes becomes limited, and therefore the**

coupled model may not produce significantly different results compared to the standalone STEMMUS-SCOPE model.

- In addition, based on our experience, calibration of the coupled framework can also be challenging due to the relatively large number of parameters and interacting processes. In this study, calibration was particularly challenging at the Loobos site, where achieving a balanced representation of water, energy, and carbon fluxes required iterative adjustments. Therefore, future studies would benefit from applying automatic or multi-objective calibration approaches as we highlighted in the revised version (lines 1092-1096) to improve parameter optimization and model robustness.

Regarding if the coupled framework readily operable and transferable to other regions

- Yes, the coupled framework is generally operable and transferable to other regions. To apply the framework, users need to prepare the required input datasets and ensure the availability of some key observations to support model calibration and validation. These required inputs and observations are summarized in Table 3 of the revised manuscript.

Regarding the key prerequisites (data, expertise) and potential pitfalls for potential users

- The main prerequisites relate to both data availability and modelling expertise. As summarized in Table 3 of the revised manuscript, the model requires meteorological forcing, soil and vegetation parameters, and hydrogeological information as inputs, as well as observational datasets for calibration and evaluation. To comprehensively evaluate the role of groundwater in the water, energy, and carbon cycles, multiple types of observations are desirable (e.g., soil moisture, soil temperature, evapotranspiration, carbon fluxes, groundwater level, groundwater temperature, and vegetation-related variables such as SIF). However, such comprehensive datasets are not always available at many sites, which may limit the depth of model evaluation. In addition, users need to be familiar with the modelling environments of both STEMMUS-SCOPE and MODFLOW 6, which may require some time and effort for new users.

Comments on the figures:

1. **Figures 3-9: Please reconsider the use of red-green color combinations, as they are not accessible to readers with color vision deficiencies. Employing a colorblind-friendly palette (e.g., blue-orange) or differentiating lines with symbols/patterns is strongly recommended.**

Agreed, we have revised all figures to use colorblind-accessible colors (orange and blue).

2. **Figures 4, 5, 6, and 9: The key comparisons between models are difficult to discern due to high data density and overlapping traces in the main panels. To improve clarity, consider 1) plotting the difference between models directly, 2) using faceted subplots for major variables, or 3) highlighting specific time periods of interest.**

Agreed, we have revised Figures 3 to 9 to improve their readability.

Authors replay to CC1: 'Comment on egusphere-2025-4179', Giacomo Medici, 29 Oct 2025

The community member comments are in **Bold black**, while the author's responses are in **bold blue**. To avoid repetitions in our replies, we apply order for the comments (1, 2, 3, etc.), to allow for cross-referencing our responses (if needed).

General comment

1. **Very good research on surface/groundwater interaction with a critical zone angle! Please, follow my guidance to improve the manuscript, and fix the issues**

Dear Dr. Giacomo Medici,
We would like to sincerely thank you for your appreciation of our work and your precious time in reviewing our manuscript and providing valuable comments that led to possible improvements in the current version. The authors have carefully considered the comments and tried our best to address every one of them. We have restructured the manuscript to clearly emphasize the scientific contributions enabled by the new modelling framework. We hope the revised version meets your expectations. Please, have a look at our responses to your comments.

Specific comment

2. **Lines 121-124. "Models typically do not account for heterogeneity in any of the aquifer properties (porous media or fractured-rock systems), which can be significant in shaping key groundwater processes such as recharge, capillary rise, and groundwater evapo-transpiration". Insert recent review papers on the role of flow heterogeneities in porous and fractured aquifers in processes that involve the recharge:**

- Zhang, H., Xu, Y., Kanyerere, T. (2020) A review of the managed aquifer recharge: Historical development, current situation and perspectives. Physics and Chemistry of the Earth, Parts A/B/C, 118, 102887.

- Agbotui, P. Y., Firouzbehi, F., Medici, G. (2025) Review of effective porosity in sandstone aquifers: insights for representation of contaminant transport. Sustainability, 17, 6469.

Okay, the mentioned relevant references are added (line 155).

3. **Line 192. Clearly state the aim of your hydrological research.**

Okay, we have expanded the research objective by adding specific objectives as explained in our reply to comment number 4.

4. **Line 192. Describe the 3 to 4 specific objectives of your research by using numbers (e.g., i, ii, and iii).**

Agreed, specific objectives are added (lines 203-209) are extended to state the novel contributions.

Lines 203-209 in revised version:

"This study aims to investigate the role of groundwater in the soil-plant-atmosphere continuum with a focus on assessing the benefits of explicitly incorporating the groundwater component in modelling soil-plant-atmosphere processes. In particular, the specific objectives are to investigate the impacts of the groundwater component (mass and energy) on: 1) regulating the soil profile, in terms of moisture and temperature, 2) the dynamics of the unsaturated/saturated zones and its further impact on water fluxes, and 3) the carbon fluxes and vegetation physiological processes (i.e. root water uptake and fluorescence)."

5. **Line 195. Provide basic description of the climate and the lithology of the region where you have applied your method. Add just a bit more.**

Thank you for the suggestion. In the revised manuscript, we have added a new table (Table 2) summarizing the main site characteristics and model discretization for the three study sites, which provides additional contextual information about the study areas. Meanwhile, we believe that the current description of the regional climate and lithology in the text is sufficient for the purposes of this study. Therefore, we respectfully preferred not to add further details in the text in order to keep the manuscript concise, especially considering that the revised version already includes additional material related to the main objectives of the study.

6. **Line 196. You should refer to the key USGS document for MODFLOW 6.**

The USGS documents of MODFLOW 6 are already mentioned earlier in lines 251-258.

Lines 251-258 in revised version:
"MODFLOW 6 is an IHM framework (Hughes et al., 2017) and is the latest "core" version of the well-known MODFLOW simulator for groundwater flow (GWF). In addition, MODFLOW 6 simulates other flow and transport processes, including unsaturated zone flow, overland flow, flow in surface features (e.g. lakes, rivers, drains, etc.), and their interaction with the groundwater system (Langevin et al., 2017; Langevin et al., 2023). Recently, a new Groundwater Energy Transport (GWE) module, patterned after the solute transport module (Langevin et al., 2022), was added to MODFLOW 6 for simulating heat transport processes within a MODFLOW 6 simulation (Morway et al., 2025) and is leveraged in this study."

7. **Line 443. KGE values not wonderful. Please, justify.**

We thank the community member for this constructive comment. We fully acknowledge that KGE values could be improved. The likely reason for the non-perfect KGE values is due to the reliance on manual calibration. While it is expected that automatic calibration would clearly enhance the statistical metrics, including KGE and reduce the uncertainties associated with manual calibration.

However, the main aim of this study was to highlight the benefits of adding the groundwater component in modelling soil-plant-atmosphere processes using a new coupling framework between STEMMUS-SCOPE and MODFLOW 6 models. Establishing the coupling framework was extensively time and effort demanding for the first author to:

c) **Adapt the STEMMUS-SCOPE code to dynamically account for the groundwater variables (e.g. bottom boundary conditions, calculations of recharge and groundwater root uptake fluxes, as explained in Methods)**
d) **Couple the two models using the Basic Modelling Interface (BMI) protocol. This was accompanied by lots of testing to validate the exchange of the variables between the two models and increase the model's credibility.**

Extensive testing was performed to ensure mass conservation and numerical consistency of the exchanged variables, which was essential to guarantee model credibility. Implementing automatic calibration within this newly developed coupling framework would require additional methodological development and computational effort beyond the scope of the present proof-of-concept study. Nevertheless, we acknowledge the importance of automatic multi-objective calibration and have explicitly incorporated this as a priority direction for future 2D/3D developments in the revised Discussion/Recommendation section (lines 1092-1096).

Lines 1092-1096 in revised version:
"Furthermore, although calibration was performed manually in this proof-of-concept study, future work should incorporate a multi-objective automatic calibration framework to systematically reduce parameter uncertainty and enhance model robustness. Implementing such an approach in future 2D/3D applications will increase confidence in predictive simulations and strengthen the broader applicability of the developed IEM."

8. Lines 695-725. Try to expand the implications of your research in the field of hydrology.

We thank the Community Member for this constructive comment. To address this, the Discussion section has been significantly expanded and reorganized to better highlight the main contributions of the study and to position the findings within the broader state of knowledge. In particular:

- **We have revised the Discussion sections into 5 sub-sections:**
  - **Soil moisture (Section 4.1.)**
  - **Soil temperature (Section 4.2.), including three separate subsections**
    - **Groundwater temperature and soil temperature (4.2.1.)**
    - **Groundwater level and soil temperature (4.2.2.)**
    - **Groundwater and surface soil temperature and canopy temperature (4.2.3.)**
  - **Evapotranspiration components (Section 4.3.), including three separate subsections**
    - **Subsurface evaporation (4.3.1.)**
    - **Root soil water uptake (4.3.2)**
    - **Root groundwater uptake (4.3.3.)**
  - **Carbon fluxes and SIF (Section 4.4).**
- **Within each Section, we have substantially rewritten the text to better highlight the contribution of the groundwater.**
- **We also added one Figure (Figure 9) in Section 4.2.3.**
- **We have also strengthened the discussion with relevant literature and, where appropriate, include comparisons with previous studies in order to place the findings within the broader ecohydrological modelling context.**

Figures and tables

9. **Figure 1. Conceptual scheme on the left; Do you need a spatial scale?**

The conceptual scheme in Figure 1 (left panel) is intended to illustrate the process interactions within the soil–plant–atmosphere–groundwater continuum rather than to represent a specific spatial domain. Therefore, a spatial scale was not originally included.

10. **Figure 1. There are two different figures. These figures should be 1 and 2.**

We thank the Community Member for this constructive observation. While the two panels of Figure 1 could be separated into independent figures, we respectfully prefer to retain them as a single composite figure. Figure 1a presents the conceptual framework of the coupling, whereas Figure 1b illustrates its methodological implementation. Keeping them together facilitates a direct visual connection between the conceptual design and its technical realization, thereby improving clarity and coherence for the reader.

11. **Figure 9. Based on that, consider to re-scale figures 3 to 9.**

Agreed, we have revised and rescaled Figures 3 to 9 to improve their readability.

12. **Figures 3, 4, 5, 6, 8, and 9. There is room to make the graphs slightly larger. You gain in readability.**

Agreed, we have revised Figures 3 to 9 to improve their readability.