We thank Reviewer #1 for the positive assessment and the helpful suggestions, which we have all adopted.

 # Review 1:

"This is an interesting paper investigating boreal crop hydraulic traits and their relevance to productivity and drought resistance in Finland, focusing on both perennial forage grass and annual oat yield. The manuscript is well structured, fits within the scope of this journal, and presents the research in a logical and coherent manner with clear figures and sound data analysis. From my perspective, the paper is suitable for publication in BG. I do not have any major comments, but I would like to provide the following minor suggestions:

This manuscript focuses on both soil drought and atmospheric drought. However, the term "meteorological drought" is also mentioned in a few places. From my perspective, this may be somewhat misleading and could make the terminology unnecessarily complicated. I suggest consistently using either "soil drought" or "atmospheric drought" throughout the manuscript."

Reply #1.1: We agree that the mixed terminology was potentially confusing. In the revised manuscript we have used "soil drought" and "atmospheric drought" consistently when referring to the two physical drivers we analyse. We have also removed the term "meteorological drought" and instead refer to the Standardised Precipitation–Evapotranspiration Index (SPEI) explicitly when identifying drought events, to avoid ambiguity.

"I suggest combining paragraphs 3, 4, and 5 into a single paragraph, since they all describe the efficiency hypothesis, safety hypothesis, and plasticity hypothesis. Similarly, paragraphs 6, 7, and 8 could also be merged into one paragraph, as they collectively describe the aims of the manuscript."

Reply #1.2: We thank the review for this suggestion to improve the flow. We have merged the three paragraphs describing the efficiency, safety, and plasticity hypotheses into a single, coherent paragraph, which now reads as following:

The text now reads:

"*However, the strength of such a trade-off is still hotly debated (Gleason et al., 2016; Sánchez-Martínez et al., 2020; Liu et al., 2021), indicating that different species adopt different positions along the efficiency–safety spectrum to improve their fitness under variable environmental conditions. For instance, common crop species (mostly annual cereal crops from temperate and tropical regions) often exhibit high hydraulic conductance (efficiency) but low hydraulic safety (Holloway-Phillips and Brodribb, 2011; Lamarque et al., 2020; Corso et al., 2020; Canales et al., 2021; Gleason et al., 2021) to obtain high crop productivity, referred to as aquisitive hydraulic strategy. This is particularly the case for annual cereals (Liu et al., 2019). On the other hand, hydraulic traits indicating high safety but low efficiency (i.e., conservative hydraulic strategy) have been widely observed in boreal tree species such as pine and spruce (Li et al., 2023). Perennial crops have been also been known for their conservative hydraulic*

strategy to survive harsh winters and tolerate more stresses (Vico et al., 2018; Liu et al., 2019). Although plant hydraulic traits are often considered relatively conserved compared with more plastic plant traits such as photosynthetic capacity (Lamy et al., 2014; Ramirez-Valiente et al., 2025), substantial phenotypical plasticity has also been found in various plants under different conditions (Pritzkow et al., 2020; Sun et al., 2021; Alves et al., 2024; Matzner et al., 2014) and growing stages (Yao et al., 2021). For example, Sun et al. (2021) showed that barley grown under conventional no-tillage management with no tillage exhibited higher hydraulic vulnerability than that under organic farming with intensive tillage."

We have also merged the paragraphs describing the aims and the model-inversion rationale into one, which now reads as following:

"*In this study, we leverage multi-year observations of carbon and water fluxes from two Finnish crop fields under a perennial forage grass mixture and an annual cereal (oats), respectively. Combining with a novel modelling framework that explicitly couples plant hydraulics, photosynthesis, and soil moisture dynamics, we infer apparent hydraulic traits of the two dominant and contrasting cropping systems in boreal agriculture, and examine their implications for crop functioning at field level. Specifically, our objective is to (i) evaluate the ability of the novel modelling framework to reproduce observed gross primary productivity and evapotranspiration, providing a basis for hydraulic trait inference; (ii) quantify and compare the apparent hydraulic traits of perennial and annual crops and assess their influence on productivity and water-use efficiency; and (iii) determine whether the two cropping systems differ in their resistance to drought and how these differences are associated with their hydraulic traits. In the following, we first describe the modelling framework, study sites and observations, and modelling experiments and workflow for addressing these objectives. We then evaluate the performance of the model, compare inferred hydraulic traits and their effects on crop functioning and drought responses, and finally discuss the broader implications and remaining uncertainties.*"

"Lines 50-51: please provide a few specific examples of crops showing phenotypic plasticity under different environmental conditions."

Reply #1.3: Thanks for the suggestion. We have added specific examples of crops showing phenotypic plasticity to this sentence:

".....*substantial phenotypic plasticity has also been documented across environmental conditions (Pritzkow et al., 2020; Sun et al., 2021; Alves et al., 2024; Matzner et al., 2014) and developmental stages (Yao et al., 2021). For example, Sun et al. (2021) showed that barley grown under conventional no-tillage management exhibited greater hydraulic vulnerability than barley grown under organic farming with intensive tillage*."

"*As far as I understand, SPY-C is not a completely new model, but rather a coupled (integrated) modelling framework that combines several existing models into one system. Therefore, instead of stating "a newly developed SPY-C model," I suggest using "a newly developed coupled modelling framework, SPY-C.*"

Reply #1.4: This is correct, and we thank the reviewer for the precise wording. SPY-C integrates three existing modules (Phydro, SpaFHy, and YASSO) with a lightweight data-driven phenology and allocation module. We have replaced "a newly developed SPY-C model" with "a newly developed coupled modelling framework, SPY-C" in the abstract, introduction, and conclusions, and have described SPY-C consistently as a coupled framework throughout.

We thank Reviewer #2 for the detailed and thoughtful review, which have prompted a number of clarifications and additions that we believe strengthen the clarity and rigor of our manuscript substantially. Following is our point-to-point response to the reviewer's comments.

 # Review 2:

"The manuscript "Plant hydraulic traits regulating productivity and drought resistance in boreal crops" written by Tang et al., explored the responses gross primary products and evapotranspiration for some crops and grasses via perturbating some aboveground plant hydraulic traits. Those traits are defined and linked to the specific modeling parameters and recently development soil-plant model. The shown data was complex with mix of measured (EC and Sentinel2 which have been published elsewhere) and simulated data for two sites with contrast soil and evaporative demand and different modeling configuration (some selected hydraulic traits).

The MS could be considered further for the publication however some critical points need to be considered: (i) clear objectives and hypothesis are required and followed by the structured results and discussion."

Reply #2.1: We thank the reviewer for this suggestion. We agree that stating the objectives explicitly, and then carrying them consistently through the Results and Discussion, will substantially improve the logical structure of the paper. We have therefore added the following three objectives at the end of the Introduction (see also Reply #1.2). Objective (i) validates the modelling framework on which the analysis rests, while objectives (ii) and (iii) directly test the hypotheses introduced earlier:

"*Specifically, our objective is to (i) evaluate the ability of the novel modelling framework to reproduce observed gross primary productivity and evapotranspiration, providing a basis for hydraulic trait inference; (ii) quantify and compare the apparent hydraulic traits of perennial and annual crops and assess their influence on productivity and water-use efficiency; and (iii) determine whether the two cropping systems differ in their resistance to drought and how these differences are associated with their hydraulic traits.* "

We have revised the Results and Discussion to follow this same order, so that the logical thread from hypotheses and objectives, through results, to interpretation becomes easy to follow.

"(ii) it is important to explain how to simulate different crop/grass traits where the sites contain many species. The name of two sites with two dominant species: GRASS and OAT are confusing and misleading since there are more species there"

Reply #2.2: We thank the review for this critical comment. This is an important point that we share, and it also recurs in several detailed comments (see also our reply #2.5, #2.10, #2.25, #2.29, #2.30). Here, we would like to clarify the conceptual basis of our approach and then describe the changes we will make.

In this study, SPY-C does not simulate each species separately. Instead, following the model-inversion literature (Liu et al., 2020), it retrieves **apparent** (effective, ecosystem-level) hydraulic traits – i.e., an average over the collective of individuals within the eddy-covariance (EC) footprint, weighted by their contribution to the measured GPP and ET fluxes. This is precisely why we use the word "**apparent**" throughout (definition at lines 67–69 of the original). In the revised manuscript, we have made this much more prominent by defining "apparent hydraulic traits" at first use in the Abstract and Introduction.

"*the field-level effective hydraulic traits (i.e., apparent hydraulic traits)*"

"*We refer to the average of the hydraulic traits over collective individuals of the same or different species at this scale as ``apparent'' hydraulic traits, in contrast to the organ- or individual-level hydraulic traits measured on single plants in the laboratory.*"

We have also added sentences in the Methods (Sect. 2.2.3) explicitly stating that the inferred traits represent effective traits at field-level rather than any single species.

"*Although the studied fields (i.e., EC flux footprints) contained mixtures of crop species, these species were spatially well mixed and were therefore represented in the model as a single effectively homogeneous canopy. This treatment is consistent with the model's field-scale representation and allows the inference of apparent hydraulic traits, whereby one effective trait set is estimated for each footprint and study period.*"

We note that at both sites, the mix of different crop species were quite homogeneous in space. They were not planted in patches. This supports that the footprints of EC tower can be treated as a homogeneous effective community.

We took the reviewers' point that "GRASS" and "OAT" can imply monocultures. So, we have renamed the sites neutrally as "Qvidja (Perennial grass mixture)" and "Hauho (Oats and cover crop)" throughout the text and figures. We have ensured that the species composition is restated in the captions of Tables 1–2 and Figs. 2, 3, 5, 6 and 10 so the naming is never read in isolation.

"(iii) The limitation of model and work have been discussed with regards of lack measurement in plant hydraulic conductance. The MS only focused on the aboveground traits and root roles did not consider or mention which are even more important in responses and adaptation."

*"*Line 25: How important of the root in the hydraulic regulation and overcome the drought?*""*

Reply #2.3: We agree that roots are central to drought response and that this deserves explicit treatment. We have clarified how roots currently enter SPY-C, and added a dedicated paragraph to Sect. 4.3 (Model uncertainties and future development):
"*A second important simplification concerns the representation of root dynamics and their influence on whole-plant hydraulics. In the current framework, K□ represents the maximum*

whole-plant hydraulic conductance per unit leaf area and therefore integrates the entire soil-to-leaf hydraulic pathway, including roots and the root–soil interface. Root hydraulic traits are thus represented only implicitly rather than as separate root, stem, and leaf conductances. Moreover, water uptake occurs from a fixed effective root zone (0.6 m in this study), while root biomass is tracked as a carbon pool but does not feed back on rooting depth, water uptake, or hydraulic conductance. Dynamic rooting depth, root distribution, hydraulic redistribution, and drought-induced changes in root hydraulic conductivity are therefore not represented. These processes can play an important role in drought adaptation of cereals and grasses (e.g., Canales et al., 2021). Coupling dynamic root growth to water uptake and hydraulic conductance, together with prognostic leaf growth, is therefore an important direction for future development. Such extensions would also allow drought avoidance mediated through root-zone dynamics to be represented more explicitly."

"*(iv) may terms and variables are mentioned. Overall, they are quite well explained however, some are not, in terms of unit and name (see below).*"

Reply #2.4: We thank the reviewer for pointing this out. We have had Table S2 in Supplement summarizing all the parameters including their units and default values. But we did not mention the table explicitly in the manuscript. We have added a clear reference to Table S2 in the revised version of the manuscript.

"*All model parameters used in SPY-C and their values for the two study fields are listed in Table S2.*"

In addition, we will also carry out a systematic pass over all model variables for naming and units. The specific unit issues raised (Figs. 8, 9, 10; lines 294–295) are addressed individually below.

Abstract
"*Line 2 Crop and grass definition*"
Reply #2.5: We have reworded the sentences in the Abstract so that they are properly separated.

".... *two Finnish fields representing contrasting boreal cropping systems---a perennial forage grass mixture and an annual cereal crop (oats)....*"

"*Line 6: what is hydraulic conductance, plant or root or stem?*"
Reply #2.6: It is the maximum whole-plant hydraulic conductance per unit leaf area (Kp), integrating the soil-to-leaf pathway. We have made this explicit in the Abstract: " …. *maximum whole-plant hydraulic conductance…."*

Introduction
"Determination and definition of hydraulic traits are still vague. What are exact hydraulic traits are you looking at?"

Reply #2.7: We have added an explicit, concrete definition early in the Introduction in the revised manuscript.

"*Among these traits, two have been most widely studied. One is maximum hydraulic conductance, which quantifies the efficiency with which water is transported through the whole plant or its individual organs (e.g., roots, stems, and leaves) to meet photosynthetic demands (Holloway-Phillips and Brodribb, 2011; Ocheltree et al., 2016; Gleason et al., 2021). The other is the water potential at which a plant loses 50% of its maximum hydraulic conductance (ψ_{50}). This trait is commonly used to quantify hydraulic safety, i.e., a plant's resistance to drought-induced embolism, loss of water-transport capacity, and ultimately hydraulic failure and mortality (Choat et al., 2012; Anderegg et al., 2016).Together, these two traits characterize plant hydraulic efficiency and safety and play a central role in shaping plant water-use strategies.*"

"See also the apparent hydraulic traits which also mentioned somewhere? What they are? i.e. in line 68-69 and line 71. Which exact scale of hydraulic traits considered in your modeling approach?"

Reply #2.8: See our reply #2.2. We have added the text to clarify "apparent hydraulic traits" and its scale in the revised manuscript.
"*In particular, using field-level flux measurements to constrain the hydraulic parameters of such models has proven effective for retrieving plant hydraulic traits at the field or ecosystem scale (Liu et al., 2020). We refer to hydraulic traits inferred at this scale, representing the collective response of multiple individuals of the same or different species, as "apparent" hydraulic traits, in contrast to organ- or individual-level traits measured on single plants in the laboratory.*"

"Line 23-24: this is not clear sentence, what is inherent structural constraints. How stomatal regulation could be a trade-off?"

Reply #2.9: We have rewritten this passage to remove the ambiguity.
"*Although plant hydraulic traits are often considered relatively conserved compared with more plastic traits such as photosynthetic capacity (Lamy et al., 2014; Ramirez-Valiente et al., 2025), ….* "

"*An analogous trade-off has also been proposed for stomatal regulation (Henry et al., 2019), whereby maximising stomatal conductance promotes carbon gain but also increases transpirational water loss and the risk of desiccating plant water potential to a damaging level.*"

"Line 25: I still do not see the diverse hydraulic strategies, especially how it is relevant for grass and oat in boreal regions. Why did you choose these two types of plants? These two plants are "grass" with stem-hollow plants, how the xylem metabolism is important in this case?

Reply #2.10: We thank the reviewer for the insightful comments.

We have revised the sentence and removed the confusing word "diverse hydraulic stratgies":
"... *However, the strength of such a trade-off is still hotly debated (Gleason et al., 2016; Sánchez-Martínez et al., 2020; Liu et al., 2021), indicating that different species adopt different positions along the efficiency–safety spectrum to improve their fitness under variable environmental conditions…..* "

We have clarified why we chose the two cropping systems (not plant types):
"*In this study, we leverage multi-year observations of carbon and water fluxes from two Finnish crop fields under a perennial forage grass mixture and an annual cereal (oats), respectively. Combining with a novel modelling framework that explicitly couples plant hydraulics, photosynthesis, and soil moisture dynamics, we infer apparent hydraulic traits of the two dominant and contrasting cropping systems in boreal agriculture, and examine their implications for crop functioning at field level. Specifically, our objective is to (i) evaluate the ability of the novel modelling framework to reproduce observed gross primary productivity and evapotranspiration, providing a basis for hydraulic trait inference; (ii) quantify and compare the apparent hydraulic traits of perennial and annual crops and assess their influence on productivity and water-use efficiency; and (iii) determine whether the two cropping systems differ in their resistance to drought and how these differences are associated with their hydraulic traits*."

We have added a notation in the Method section why xylem hydraulics remains essential for long-distance water transport in grasses:
"*Note that although the hydraulic framework underlying P-hydro was developed primarily in the context of woody plants, its principles are also applicable to grass-like crops, where water is transported through functional xylem vessels within vascular bundles that provide a continuous hydraulic pathway from roots to leaves, despite the hollow stem structure and absence of secondary woody tissues (Heckwolf et al., 2015)*."

Line 64: the reference was a bit too less, there are more work ongoing (to include plant hydraulic into crop models) in this topic.

Reply #2.11: Thank you for the suggestion. We have expanded the citations here to better reflect the growing body of work coupling plant hydraulics with crop models, such as Wang et al. (2020), Gleason et al. (2022) and Kubota et al. (2026):
"*Process-based models with an explicit representation of plant hydraulic processes have emerged only recently and have been shown to better describe plant responses to drought, especially atmospheric drought, than models without hydraulic processes (Kennedy et al., 2019; Liu et al., 2020; Kubota et al., 2026; Hu et al., 2026). They are also shown to be valuable tools for revealing plant's hydraulic traits through model inversion or calibration (Wang et al., 2020; Gleason et al., 2022; Liu et al., 2021; Lu et al., 2022).*"

"Line 75: you said "our hypotheses" what are they? Or do you mean the summarize of three hypotheses that you draw out from the existing literatures i.e. safety, efficiency, and plasticity?

One needs a better and clear hypothesis, objectives and how they are related to the clearly defined hydraulic traits. Look at the results section, the results are not so well structured and clearly link to the hypotheses and objectives."

Reply #2.12: We agree with the reviewer that our hypothesis and objectives are not clearly linked to the results sections. We have revised the Introduction to present clearer objectives that are reflected in the results sections consistently. Please see also our reply #2.1.

Materials and methods
Line 86: how about the other component of plant conductance? Root, stem?
Reply #2.13: Please see our Reply #2.3. Kp is the maximum whole-plant conductance lumping root, stem, and leaf resistances together. The model does not partition among them. We have stated this explicitly at the definition of Kp and cross-referenced the limitation in Sect. 4.3 in the revised version of the manuscript.

"*Kp (m) is the maximum whole-plant conductance per unit leaf area, which lumps the entire soil-to-leaf hydraulic pathway (including root, stem, and leaf) into a single effective conductance.*"

"*A second important simplification concerns the representation of roots dynamics and its influence on whole-plant hydraulics. In the current framework, Kp represents the maximum whole-plant hydraulic conductance per unit leaf area and therefore integrates the entire soil-to-leaf hydraulic pathway, including roots and the root--soil interface. Root hydraulic traits are thus represented only implicitly rather than as separate root, stem, and leaf conductances.*"

Line 88: how estimate the gs and which one is leaf and/or plant water potential? It is not clear to me the gradient of water potential in the plant or canopy.

Reply #2.14: gs is not prescribed; it is solved as part of the optimality calculation. Phydro finds the gs (equivalently the stomatal-regulated Δψ) and Jmax that maximise the net carbon profit F (Eq. 10), subject to the steady-state leaf water balance (Eq. 1) and CO2 balance (Eq. 9). The relevant water potentials are: ψs = soil (root-zone) water potential, derived from simulated soil moisture via the van Genuchten retention curve (Eq. 13); and ψleaf = ψs − Δψ, the leaf water potential, where Δψ is the soil-to-leaf potential drop. We have clarified the definitions of ψs, ψleaf, and Δψ explicitly at Eqs. 1 and 9.
"ψ_s (Pa) is the soil water potential. $\Delta\psi$ (Pa) is the difference in water potential between the soil and the leaf (i.e., $\psi_{soil} - \psi_{leaf}$). "

Line 100: Vcmax, how do you estimate the carboxylation capacity of leaves? Is it from Rubisco?

Reply #2.15: Vcmax is also emergent, not prescribed. It follows from the photosynthetic-coordination hypothesis (Eq. 4): the carboxylation-limited rate Ac is set equal to the light-limited rate Aj at the prevailing light, temperature, CO2, and the optimised Δψ and

Jmax. This determines the acclimated Vcmax without assuming a fixed leaf Rubisco content. We have clarified this in the text:
".....Vcmax, Rd, and gs can also be derived according to Eq. 4, 5, and 1, respectively, once Jmax and $\Delta\psi$ are determined."

Line 105: how the soil water status is updated (after one day, one hour, one week) and how did it link to photosynthesis? This is more important.

Reply #2.16: The SpaFHy soil-water balance is updated at hourly resolution, the same time step as Phydro, so that photosynthesis and transpiration are tightly coupled to soil moisture within the day. At each hourly step the updated volumetric soil moisture is converted to ψs (Eq. 13) and passed to Phydro, which then solves gs, GPP, and transpiration through Eq. 1. The transpiration in turn withdraws water from the soil stored in the next time step. We have made this hourly two-way coupling explicit in Sect. 2.1.5 and in the new Figure 1.

"*As shown in Fig. 1, SPY-C runs on two nested time steps. Phydro and SpaFHy are integrated hourly and two-way coupled: each hour, SpaFHy's soil moisture is converted to soil water potential before passing to Phydro; Phydro solves stomatal conductance and thus transpiration (Eq. \ref{eq:phydro_tran}); the transpiration is then sent to SpaFhy and is withdrawn from the soil water store together with soil evaporation, updating soil moisture for the next hour.* "

Line 125: How do you measure the alpha and gamma parameters and at which scales?
We need of table with variable name of parameters with unit and used values for the calibration and validation work for different plant types.

Reply #2.17: α (unit cost of maintaining photosynthetic capacity) and γ (unit cost of maintaining the hydraulic pathway) are not measured. They are theoretical cost coefficients in the optimality framework of Joshi et al. (2022). Their values are inferred at the field/ecosystem scale by selecting the parameter-perturbation ensemble (PPE) members that best reproduce the observed GPP and ET of the EC footprint. We have clarified this in the revised version of the manuscript:

"*α is a unitless coefficient denoting the unit cost of maintaining photosynthetic capacity, such as the regeneration of RuBP and electron transport proteins. γ ($\mu mol\ m^{-2}\ s^{-1}\ Pa^{-2}$) denotes the unit cost of maintaining the plant hydraulic pathway, such as the construction cost to build xylem vessels and fibres. Both are conceptual parameters that are inferred rather than directly measured.*"

All the model parameters including their units and default values for the two study sites have been listed in Table S2 in Supplement.

Line 135: It seems that the model treats LAI as single canopy that do not separate the photosynthesis, transpiration over different leaf types and depths?

Reply #2.18: This is correct. SPY-C uses a big-leaf representation: a prescribed total one-sided green LAI (from Sentinel-2) with within-canopy light attenuation via Beer's law (Eq. 8) and per-leaf-area absorbed PAR scaled by LAI (Eq. 7). It does not resolve sunlit/shaded fractions or multiple canopy layers. We have stated this explicitly and added it to the limitations in the revised version of the manuscript.

"*LAI (m2m−2) is the total one-sided green leaf area per unit ground surface area, and fapar is the fraction of absorbed photosynthetically active radiation by the plant, which can be approximated following Beer's law …. For simplicity, the model does not resolve sunlit/shaded leaf fractions or multiple canopy layers.*"

"*Several structural simplifications in the current version of SPY-C may contribute to uncertainties in the simulated carbon and water fluxes and the inferred apparent hydraulic traits. First, SPY-C adopts a big-leaf canopy representation, in which prescribed total one-sided green LAI is combined with within-canopy light attenuation using Beer's law. The model therefore does not explicitly distinguish sunlit and shaded leaves or resolve multiple canopy layers. This simplification may contribute to biases in the diurnal partitioning of GPP and ET, particularly during the early morning and late afternoon (Fig. 5). A two-leaf or multilayer canopy representation could improve the treatment of within-canopy radiation and associated carbon and water fluxes.*"

Line 149, soil to root water potential was estimated? And how root play a role here? What is belowground boundary of model and simulation?

Reply #2.19: Soil water potential ψs is computed from its volumetric moisture via van Genuchten (Eq. 13). There is no explicit estimation of root water potential in our model. Root water uptake from soil is merely the transpiration demand met from this layer, and root water conductance has been lumped into whole-plant hydraulic conductance (Kp). The belowground boundary of the model (i.e., the boundary below soil layer) is free drainage according to Ksoil when soil water potential is above field capacity. We have clarified the belowground boundary of soil and how roots play a role in water balance in the revised version of the manuscript:

"*When soil water potential is above field capacity, free drainage according to K$_{soil}$ can occur at the lower boundary of the soil in SpaFhy. There is no explicit estimation of root water potential. Root water conductance has also been lumped into whole-plant hydraulic conductance (K$_p$) in Phydro. Root water uptake from soil is merely the transpiration demand given by Phydro met from the total soil water storage simulated in SpaFhy*."

Line 158: how ET is calculated? How to link the evaporative demand with soil and plant root water uptake. What is the aboveground boundary?

Reply #2.20: Total ET = canopy interception evaporation + soil/ground evaporation + plant transpiration. Transpiration is computed by Phydro (Eq. 12, Tr = 1.6 gs D · LAI), i.e., it is driven

by atmospheric demand (VPD) but constrained by the supply through the left-side of Eq. 1 and hence by ψs and Kp — this is the supply–demand coupling. Canopy interception evaporation and soil evaporation follow the SpaFHy formulations, and calculated using Penman-Monteith equation (interception evaporation) and soil-water availability - restricted Priestley-Taylor approach (soil evaporation). The aboveground boundary condition is the meteorological forcing (radiation, T, VPD, CO2, precipitation, wind, air pressure) at the canopy top. We have spelled out the equation for calculating ET from the three components in the revised version of the manuscript:

"*The calculation of canopy interception evaporation and soil evaporation follow the SpaFHy formulations, using Penman-Monteith equation and soil-water availability restricted Priestley-Taylor approach, respectively. Total ET is the sum of canopy and soil evaporation given by SpaFhy, and transpiration flux given by Phydro (Fig. 1).*"

Line 160: how the phenology was simulated as the authors mentioned here

Reply #2.21: Phenology is prescribed, not dynamically simulated: the seasonal canopy development is imposed through the daily LAI interpolated from Sentinel-2 (Fig. 2c,d), and management events (harvest, grazing, fertilisation) are imposed on the prescribed dates shown in Fig. 2. The PA module then allocates daily GPP to leaf/root/grain pools (Eqs. 16–18). We have state clearly that canopy phenology is observation-driven rather than prognostic:

"*In the current model version, phenology is prescribed rather than dynamically simulated: the seasonal canopy development is imposed through the daily LAI interpolated from Sentinel-2 product (Fig. 2c,d), and reported management events (e.g., harvest, grazing, fertilisation).* "

Line 165: how root growth and root distribution are simulated and used in the other modeling routine and how it relates to the hydraulic traits

Reply #2.22: Please see also our reply #2.3. Root carbon is tracked as a prognostic pool (Eqs. 17, 20) subject to allocation, respiration, and turnover, and it supplies litter to soil decomposition model YASSO. However, this root carbon does NOT dynamically change rooting depth or hydraulic traits: the root-zone depth (0.6 m) and Kp are fixed within a simulation and root profile implicitly assumed constant with depth in accordance with the soil water bucket approach. Hence root growth currently feeds the carbon/soil-carbon cycle but is decoupled from the water/hydraulic routine. We have made this explicit in the revised version of the manuscript:

"*Note that root carbon is tracked as a prognostic pool (Eq. 20) subject to allocation, respiration, and turnover, and it supplies litter to soil decomposition model YASSO. However, this root carbon does NOT dynamically change rooting depth or hydraulic traits: the root-zone depth (0.6 m) and Kp are fixed within a simulation, hence is decoupled from the water/hydraulic routine in the model.*"

Line 192: there are different modeling routines in the whole model which are different from temporal resolution (hourly, daily) how do the sub-model link at that point and how the soil-plant-atmospheric are coupled. I did not see the role of root and set-up of below and above boundary of the model. How dynamics of root growth, leaf area growth contribute to the simulation of water and carbon fluxes.

Reply #2.23: We thank the reviewer for this question, which prompted us to describe the model coupling, boundaries, and treatment of roots/leaf area more explicitly. We have improved Fig. 1 and added a dedicated "Model coupling" section Sect. 2.1.5 to address the issues raised by the review in the revised version of the manuscript:

"*As shown in Fig. 1, SPY-C runs on two nested time steps. Phydro and SpaFHy are integrated hourly and two-way coupled: each hour, SpaFHy's soil moisture is converted to soil water potential before passing to Phydro; Phydro solves stomatal conductance and thus transpiration (Eq. 12); the transpiration is then sent to SpaFhy and is withdrawn from the soil water store together with soil evaporation, updating soil moisture for the next hour. The PA and YASSO modules run daily: hourly GPP is accumulated to a daily total, allocated by PA to leaf, root, and grain pools (Eqs. 16–18), and the resulting litter drives YASSO, yielding RECO and NEE on daily scale (Eqs. 22–23). The hourly to daily link is GPP accumulation, while the daily to hourly link is the prescribed canopy state (i.e., LAI). Daily leaf area growth enters the hourly P-hydro calculations through absorbed PAR (Eqs. 7–8) and is used to scale GPP and transpiration to the canopy level (Eqs. 11–12). It modulates both carbon and water fluxes every hour as an observation-driven boundary condition (Fig. 1), rather than as a prognostic variable linked to primary productivity and soil moisture. Consequently, two-way coupling between PA and P-hydro/SpaFhy is not yet fully implemented in the current version of SPY-C.*"

Line 196: What are the mineral soil crop fields? It is not clear writing.

Reply #2.24: "Mineral soil" is used in contrast to organic-rich peat soils, which are common and agronomically important in Finland and behave very differently in both its hydrology and carbon cycle. We chose two mineral-soil fields to keep the soil carbon and water dynamics within the regime for which SPY-C/YASSO is parameterised. We have reworded the text to "Two agricultural fields on mineral (i.e., non-peat) soils in Southern Finland" in the revised version of the manuscript.

Line 197 and 202: there are mix crops and do not know how big shares of crop are? The name of sites in 205 did not sound reasonable, see 225.
Line 225: The names are confusing and not correct because the footprints contain mix of species. It is not sure how the model treated this difference in terms of species within footprint.

Reply #2.25: Please see also our Reply #2.2. We would like to clarify that the mix crops here mean mixed species sown in the field. They did not grow in patches but well mixed, thus can be treated as an effectively homogeneous canopy**.** We have clarified that the model treats each

footprint as one effective community and infers apparent traits at field level. It does not assign separate traits to individual species.

"*Although the studied fields (i.e., EC flux footprints) contained mixtures of crop species, these species were spatially well mixed and were therefore represented in the model as a single effectively homogeneous canopy. This treatment is consistent with the model's field-scale representation and allows the inference of apparent hydraulic traits, whereby one effective trait set is estimated for each footprint and study period.* "

Line 224: is it similar for both sites? The data showed differently for two sites

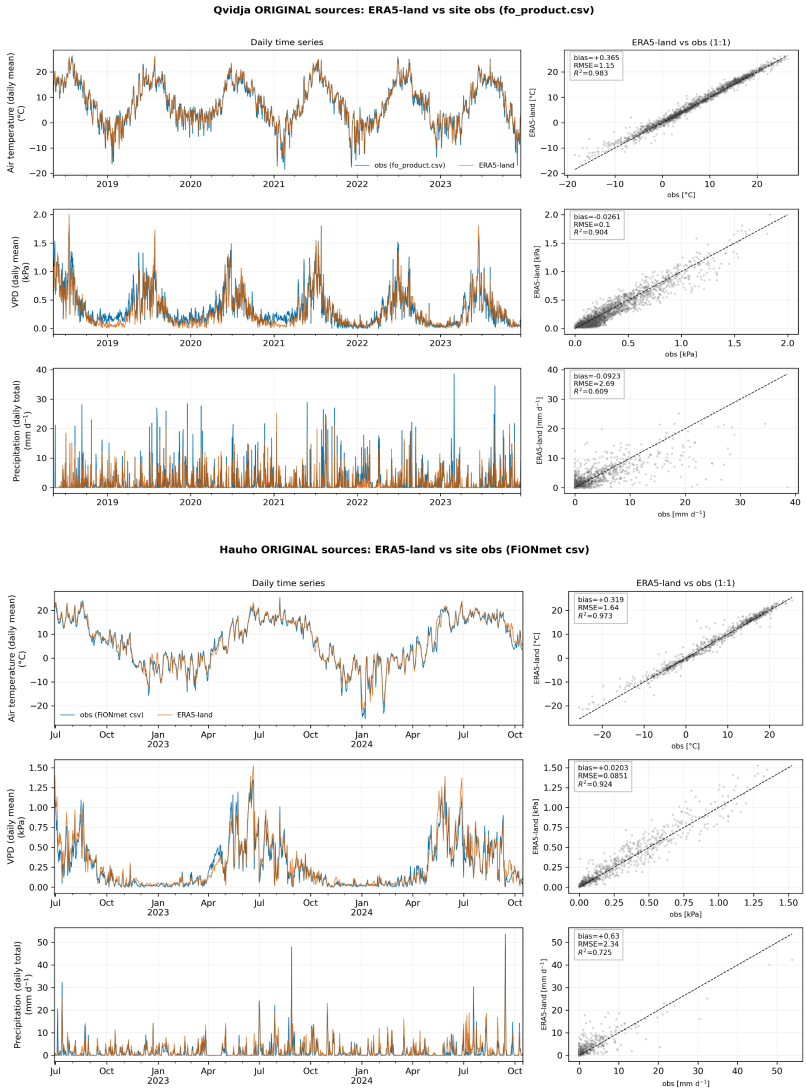
Reply #2.26: The simulations were set to start on 01.01.2018 for Qvidja and 01.01.2022 for Hauho, respectively. Both simulations ended on 31.12.2023. The meteorological forcing data for the two sites were retrieved from ERA5-Land reanalysis data using their geographical locations. They are indeed different. We have reworded the sentence to make the message clearer:

"*The simulations were set to start on 01.01.2018 for Qvidja and 01.01.2022 for Hauho, respectively. Both simulations ended on 31.12.2023.*"

Line 225: this did not make sense. There were the measurements of climate data at the EC but why the authors use the ERA5 data which could result many uncertainties for modeling results. Any check or compared for the location data?

Reply #2.27: This is a fair concern. We used ERA5-Land forcing for three reasons: (a) it provides a gap-free, internally consistent set of all required drivers (radiation, T, VPD, precipitation, wind, pressure) over the full simulation period, whereas the on-site meteorological records contain gaps and do not cover every required variable; (b) it makes the workflow transferable to sites and periods without complete in-situ meteorology, which is our intended application (MRV); and (c) for the variables that matter most to the hydraulic response (T, VPD, radiation) ERA5-Land agrees well with the on-site measurements (see the following figure). We indeed tested the model using the local observation data, and the results are quite similar. We have added a sentence justifying the choice in the revised version of the manuscript:

"*ERA5-Land was used because it provides a gap-free and internally consistent set of all meteorological drivers required by SPY-C over the entire simulation period. Its use also facilitates the transferability of the modelling framework to sites and periods without complete in-situ meteorological observations, which is important for its intended application in the future. ERA5-Land showed good agreement with the on-site measurements for the key meteorological variables at our study sites, such as air temperature, precipitation, and VPD (data not shown).*"



Line 226: Since the footprint has mix of crop and species, how the authors differentiate the LAI based on the Sentinal-2. This is very critical. How the crop map was used in the foot-print? Did the authors have the detailed crop map?

Reply #2.28: Sentinel-2 gives a total single-sided green LAI per pixel (20x20 m). We do not attempt to split it by species, consistent with our apparent-trait, big-leaf approach (see also our Reply #2.2). The LAI used is the footprint-aggregated total LAI, which is the correct quantity to drive a big-leaf canopy and to compare against the footprint-integrated EC fluxes.

There may have been some unclear description and misinterpretation, as the entire footprint area consisted of similar vegetation dominated by the species in question, and thus did not, for example, consist of subareas dominated by different species. As different species are well-mixed and are not grown in patches, we did not use a per-species crop map. We have

stated explicitly that the total (not species-resolved) single-sided LAI is used and why this is consistent with the apparent-trait framework in the revised manuscript.

"*The retrieval provides total single-sided green LAI at 20×20 m, which was then aggregated over the EC flux footprint at each site to obtain a field-level total LAI used to drive the model. This aggregation is consistent with the model's big-leaf canopy representation and with the spatial scale at which modelled fluxes were compared with EC observations.*"

Table 1 and Table 2 are confusing, while the author emphasized two locations with GRASS and OAT, the table mentioned again different crops and grass which is very inconsistent to the text. It is really not clear whether the study simulate single plant or mix of plant per site or all sites.

Reply #2.29: We have made the tables internally consistent with the two-site framing and with the apparent-trait concept (See our Reply #2.2). Specifically, Table 2 (Old Table 1) now groups the best-fit parameter sets under the two sites, and we modified "perennial grass" to "*Perennial grass mixture (Qvidja)*" representing the EC footprint community of the Qvidja site; "Oat" to "*Oats (cash crop, Hauho)*" emphasizing the EC footprint of Hauho during periods when oats grow; "Cover crop mixture" to "*Italian Ryegrass (cover crop, Hauho)*" to denote the specific period at the Hauho site dominated by the undersown annual Italian ryegrass. We have also added a caption sentence: *"Each parameter set is an apparent, field-level trait set for the dominant community of the corresponding footprint/period, not a single-species value.*" We hope this removes the apparent inconsistency.

Line 199, did the authors simulate different grass, legume, oat, clover, rye grass? It is not clear, for which analysis and objectives?

Reply #2.30: See also our reply #2.2, #2.25 and #2.28. No–we did not run separate species simulations. The species listed (timothy, meadow fescue, white clover at Qvidja; oat and undersown Italian ryegrass at Hauho) describe the observed footprint composition. The model infers one apparent trait set per footprint/period.

Figure 2b, it is not clear the range of SWC for two locations, look like Qnidja with purple color has very high SWC, around 0.5 cm3 cm-3, or the legend did not show clearly. For the LAI in 2c, it should be clear how to create the interpolated LAI, especially the off-seasons

Reply #2.31: We have improved Fig. 2: (a) We have relabelled and re-coloured the Qvidja/Hauho measured-SWC envelopes and clarified the legend (b) We have added to the caption (and Methods) that the daily LAI was obtained by Gaussian-process-regression interpolation of the Sentinel-2 retrievals (Vira et al., 2025). We have stated this explicitly so the winter values are not misread. We also note that although the off-season LAI has larger uncertainties, its impact on GPP is small:

"*Gaussian process regression was used for temporal interpolation of satellite-derived LAI because it can accommodate irregularly spaced observations while providing both a smooth interpolation and an explicit estimate of prediction uncertainty. In the presence of data gaps, the interpolation gradually approaches the mean of the Gaussian process, which was set to zero. This approach was found to perform well under Finnish conditions (Vira et al. 2025), since extended data gaps were almost exclusively during winter, when the fields were snow-covered and LAI was effectively zero. These gaps are reflected in the larger prediction uncertainty of the interpolated time series.*"

Line 263, the Ψ50 is the leaf water potential or stem water potential? For the herbaceous crops or grass, -3 MPa is already too low that plant might be almost wilt thus the lost of hydraulic conductance at this threshold might be too low for 50% reduction.

Reply #2.32: ψ50 here is the water potential of the whole-plant vulnerability curve (Eq. 2), expressed on the same water-potential basis as ψleaf, not a stem-specific value. We agree −3 MPa is at the conservative (safe) extreme for herbaceous crops; it is the lower bound of the prior range [−3, dd−1] MPa, deliberately set wide to avoid prematurely excluding values.

Line 294 and 295, units?

Reply #2.33: We have added the missing units. pWUE (Eq. 26) = GPP/Tr is in μmol CO2 (mmol $H2O)^{-1}$ (or, equivalently, the unit shown in Fig. 5); iWUE (Eq. 27) = (Aj+Rd)/(1.6 gs) is in μmol CO2 (mol $H2O)^{-1}$. They are consistent with the axis labels in Figs. 6 and 9 in the revised manuscript.

Section 2.2.3, it is not clear the table 2 should belong to the results. Also, it is not clear how the modeling sensitivity analysis and perturbation contribute to the objective and hypothesis (see repetition in section 3.2)

Reply #2.34: Table 2 defines the experimental design (the seven PPE experiments and their settings), so we have kept it in the Methods. The modeling sensitivity analysis and perturbation will serve the newly added objectives well (Please see our reply #2.1). More specifically, the PPE + best-fit selection serves the **inversion** (which traits the crops have), while the Morris sensitivity analysis on the same ensemble serves the **attribution** (how each trait affects GPP/ET/WUE and the soil- vs atmospheric-drought response). We have added a new workflow figure (Fig. 3 in the revised manuscript) to better illustrate the purposes of perturbation experiments and sensitivity analysis.

It would be better to provide a diagram to show the work flow. It is really confusing there with two sites with different soils and SWCT, different growing seasons, initialization, different PPE with soil moisture and VPD then different bet-fist of parameters. It is complex to follow up the information.

Reply #2.35: We agree, and thank the reviewer for the suggestion. We have added a workflow/experimental-design schematic figure (Fig. 3 in the revised manuscript) showing how PPE experiments per site (ctrl/swrc3/fullSM/noVPD) were designed and how best-fit selection (inversion) and Morris sensitivity (attribution) were done, respectively for what objectives.

Results and discussion
Line 305: The figure must be right away after the first mentioned text.
Reply #2.36: We have adjusted the figure placement so that each figure appears as close as possible after its first citation.

Line 312: now the crop mixture comes, how the simulation was done with crop mixture and how hydraulic traits were considered?
Reply #2.37: This refers to the cover crop (Italian ryegrass) period at the Hauho site. As with the other footprints, we did not simulate species individually. We inferred a separate apparent trait set for the cover crop dominated period. We have clarified this in the newly added workflow figure (See Reply #2.35) and the revised text (Please see also our Reply #2.2, #2.25 and #2.28).

Line 320: "diurnal"
Reply #2.38: Thanks for noticing the typo. It has been corrected.

Figure 3: what does it mean "grass (all), "Oat (all). Why there is no red and blue crosses in c) and d)
Reply #2.39: We have removed subplots (a)-(d) to avoid the confusion.

Figure 4: from which best fit parameters? There are different ones? Or mean of different best fit parameter sets.
Reply #2.40: Fig. 4 (Figure 5 in the revised manuscript) shows the average of the five best-fit PPE members for each site using QV_ctrl and HA_ctrl — the violins show the spread across days, not a single set and not a single mean. We have stated this explicitly in the caption.

Figure 5. The author mentioned the measured soil moisture content at 5-10 cm soil depth, I did not see the measured soil water content here. And which simulated SWC are shown here in 5i and 5j. See also the figure 6., which soil depth or over soil profile? How is to determine the wilting point? It is confusing to use the inconsistent term: best fit parameter and five best fit parameters for the results.
Reply #2.41: Figs. 5i,j (Figure 6 in the revised manuscript) shows the modelled root-zone (0–0.6 m, single-layer) soil moisture across the PPE, with the average of the best-fit members as red circles. The model's single bulk layer is not directly comparable to a point soil moisture sensor at 5–10 cm. We therefore did not overlay the point measurement in the violin panels. To address the comment we have stated explicitly in the caption that 5i,j show modelled bulk root-zone soil moisture (θ), and the modelled-vs-measured soil moisture has been provided in Fig. S1 in the Supplement. In Fig. 6 (Figure 7 in the revised manuscript), sensitivities are likewise for the modelled bulk root-zone soil moisture.

Wilting point shown in Figs. 5i,j is defined as the soil moisture at a reference matric potential (−1.5 MPa). We now state this definition explicitly where the wilting point is first used and in the captions. To remove the "best-fit parameter" vs "five best-fit parameter" inconsistency, we have used a single consistent phrase — "the five best-fit parameter sets" — throughout, and defined it once in Methods.

Figure 8: check the units of variables, micromole C?

Reply #2.42: Thanks for noting this. We have corrected the units in Fig. 8 (Fig. 9 in the revised manuscript). The assimilation rate, Vcmax, Jmax, etc. are all in μmol CO2 m^{-2} s^{-1} to be consistent with the units of pWUE/iWUE which use μmol CO2 (not μmol C). We note that in our model, stomatal conductance (gs) has the unit of mol CO2 m-2 s-1.

Figure 9: Figure 9a needs unit of plant water conductance to avoid the ratio unit

Reply #2.43: Thanks for noting this. Fig. 9a (Figure 11a in the revised manuscript) now shows plant water conductance with its physical unit (10^{-16} m).

Figure 9c uses the same term ET or transpirations like in other graphs

Reply #2.44: The quantity in Fig. 9c is Transpiration ratio (between simulations with higher Kp and that with lowest Kp), not the absolute transpiration values.

Why the change of GPP is much less compare to change of ET when increase in plant water conductance. The GPP in 9b even still maintains or increase around 2 %? There will be no reduction of GPP due to the soil water reduction as sequence of high plant hydraulic conductance

Reply #2.45: This is exactly the central mechanism the figure is meant to illustrate, and the behaviour is physically expected. Increasing Kp relaxes the hydraulic supply limit, so transpiration responds strongly with changing hydraulic conductance (large change in panel c), but the carbon gain saturates because photosynthesis becomes light/biochemistry-limited rather than water-limited — hence GPP changes little (panel b). A faster decline of GPP (ratio from 1 to 0.88) indeed occurs when soil moisture is below the wilting point (i.e., <-1.5 MPa) and soil water limitation becomes significant. But in this regime, the decline of transpiration is even faster. We have added some text to describe GPP reduction with the decline of soil moisture more precisely:

"*Under soil drought, high hydraulic efficiency accelerated soil-water depletion and lowered soil and plant water potentials (Fig. 11a). The resulting decline in hydraulic conductance reduced both GPP and transpiration, but transpiration declined more strongly, thereby increasing pWUE (Fig. 11b-d). GPP remained relatively insensitive until soil water potential fell below approximately the wilting pont (*-1.5 *MPa), after which photosynthesis also declined more markedly."*

Figure 10 now shows for different crops and grass which should be somewhere in very beginning. Why now measured data for oat in 10e. Why plant conductance has unit in m (see also somewhere in the materials and methods).

Reply #2.46: Thanks for the suggestion. We have moved Fig. 10 to the first part of the discussion according to the suggestion.

Panel (e) does not show measured data for oat because in the original study, i.e., Canales et al. (2021), oat (Avena sativa) leaf hydraulic conductance was not measured. This study only measured root hydraulic conductance (no root water potential measured), and it is unclear in the paper if the root measurements were done using the same plants with leaf water potential measurements. This makes it impossible to link the leaf water potential (the X-axis) with the root hydraulic conductance in the plot.

We use “m” as the unit for plant hydraulic conductance to be consistent with that used in Phydro formulation (Eq. 1) (Please see also our reply #2.4). Indeed, in most of the literature, hydraulic conductance is in a different unit, such as mmol m-2 -s Mpa-1. Therefore, we have listed the values using different units in Table S3 in the Supplement. We would like to refer to that table, if the readers are interested in checking the values of hydraulic conductance in different units.