Reply to referee 2

Dear reviewer

Thank you for carefully reading our manuscript and providing valuable comments. We reply to each of your comments below (in blue text)

Comment: This manuscript investigates the sensitivity of soil landscape evolution in a typical transitional area that is vulnerable to environmental change. It is an interesting work which is based on robust digital soil mapping (DSM) at multiple depths, and then the evolutionary pathway analysis. The latter part is especially meaningful and brings new insights into how we can make DSM more useful, and how to rationally understand and interpret the soil maps. Such perspective is rarely considered by the large amount of DSM studies, and the attempt to move beyond static DSM to dynamic landscape evolution analysis using the Δ complexity metric is a valuable direction. However, the manuscript still needs to be improved in several aspects. Following includes specific comments.

Authors: Thank you very much for your thoughtful and constructive comments on our manuscript. We are truly encouraged by your positive recognition of our work. Your observation that most DSM studies remain static is highly perceptive, and it exactly reflects our motivation for this study. Your affirmation convinces us that this direction is worth pursuing further. We have carefully read your comments, and we fully agree that the manuscript needs further improvement in several aspects.

Major comments

Comment: The core for determining evolutional pathway is the changes of soil complexity among various depths. But this issue is not sufficiently described in the Introduction, which makes readers easy to get lost when encounter this in the method part. Specifically, complexity has not been mentioned in the Introduction, although it is so important for the manuscript and it is highlighted in the title. Such core term and theory should be better defined and introduced. For example, what is the link between complexity differences and the pedogenetic processes?

Authors: Thank you for your comment. You are right that the concept of soil complexity - and especially its changes across depths - is the very core of our evolutionary pathway analysis, yet it was not adequately introduced in the Introduction. We recognize that this omission could indeed confuse readers when they encounter the metric in the Methods section, and we fully agree that the term should be clearly defined and theoretically grounded from the outset, particularly given its prominence in the title. The definitions of some terms are as follows:

1.Complexity: We calculate complexity as the spatial standard deviation of a soil property x at a certain depth d within the catchment.

2.ΔComplexity: The Δ complexity is calculated as the difference in complexity value between two layers, divided by the corresponding depth interval between the two layers.

3.Divergence: Negative values of the Δ complexity indicate a divergent change in soil properties, meaning that the lower layer is more heterogeneous than the upper layer and that its complexity value is larger than that of the upper layer.

4.Convergence: Positive values of the Δ complexity indicate the convergent change in soil

properties, meaning that the lower layer is more homogeneous than the upper layer and that its complexity value is smaller than the upper layer. Convergent and divergent, the ∆ complexity they describe is merely a superficial manifestation, and it only serves as a metric for determine sensitive areas.
Due to the lack of chronological data, we have made changes to Van der Meij's method in the manuscript and tried to avoid mentioning evolutionary pathway as much as possible.

Comment: The study uses spatial heterogeneity (∆ complexity) to infer temporal evolution ("evolutionary pathways") without any chronological control (e.g., radiocarbon dating). The link between spatial variance and temporal trajectory is asserted but not proven. You cannot robustly infer temporal evolution trajectories solely from spatial variance without independent age control. High heterogeneity might indicate active erosion, but it could also simply reflect mixed parent material. You must significantly tone down the claims of "evolutionary pathways." Reframe the study as an analysis of spatial heterogeneity patterns that suggest potential instability or mixing, rather than definitive evolutionary trajectories.
Authors: Thank you for your comment. We know that there is no chronological data in the manuscript, so we try to avoid mentioning time in the text. However, we will add some cautious descriptions of time in the future.

Comment: Why authors modify the approach of Van der Meij (2022)? The reasons should be well addressed in 2.5. The 148 catchments should be mentioned in this part because authors calculate the complexity based on such spatial units. How these 148 catchments were determined should also be introduced.
Authors: We appreciate your reminding. We apologize for failing to elaborate on the reason behind our modification of Van der Meij (2022)'s method in the Methods section. We will clarify this in section 2.5. Because Van der Meij (2022)'s method involves time, and our study lacks chronological data, we replaced the time in the method with depth intervals to convert the temporal metric into a spatial metric. The catchment boundaries in this manuscript were delineated by processing DEM data via the Spatial Analyst Tools ->Hydrology within ArcGIS.

Comment: What does the sensitive and highly sensitive areas refer to? What are the differences between them? This should be more clearly described or defined in 2.6 or other parts of the manuscript. You need to validate these "sensitive areas" with ground truth. Do these areas actually show signs of erosion (rills, gullies) or degradation in the field? Without field validation, "sensitive area" is just a theoretical construct. Add a section validating your map against actual erosion features or land degradation signs.
Authors: We appreciate your comment. Sorry for not clearly stating it in the manuscript. We will distinguish between sensitive and highly sensitive areas in the manuscript. The sensitive area is determined by horizontal heterogeneity and underlying surface conditions. Specifically, ∆ complexity is calculated for both shallow (subtract 20-25 cm from 0-5 cm) and deep (subtract 35-40 cm from 25-30 cm) layers across all catchments in the study area. Catchments exhibiting different transformation directions with larger discrepancies between deep and shallow layers are then evaluated in combination with underlying surface conditions—including parent material, topography, and vegetation—to ultimately determine the three sensitive areas. Highly sensitive

area is further identified from the previously determined sensitive areas based on vertical heterogeneity. Specifically, Δ complexity is calculated layer by layer from 0-40 cm at 5 cm intervals. More frequent shifts between positive and negative Δ complexity values from topsoil to subsoil indicate stronger vertical heterogeneity. Catchment within sensitive areas that exhibited strong vertical heterogeneity were designated as highly sensitive area.
Thank you for your valuable suggestion. All sample data used in this study were obtained through field measurements. The sampling process involved soil drilling, so each sampling point can be regarded, to some extent, as a mini-profile. It is our view that such samples provide ground truth. Moreover, in this study we mapped and analysed heterogeneity for both clay content and X_{lf}; the sensitive areas derived from these two independent soil properties are mutually corroborative, which we hope adds some confidence to our interpretations. The convergent and divergent described in this amnuscript are directional, that is, whether it is convergent or divergent from upper to lower levels. If there is a large amount of accumulated material, it will actually be written as divergent in this article, because the upper layer receives more homogeneous soil accumulation, which will be more uniform than the lower layer.

Comment: In 2.3, it would be much better to first give a whole idea about what properties authors want to measure and tell readers why. Then, continue with the specifics. Such information might also be mentioned in 2.2, then it is easier to understand why authors implement soil sampling in that way.
Authors: We thank the reviewer for the careful reading. We will add a general overview of the measured properties at the beginning of Section 2.3, and then provide the specific reasons afterwards. Such as "Pedogenesis can substantially affect soil physical properties, especially clay content and $\chi_{lf.}$ Thus, measuring these two properties allows us to gain critical information about soil formation and landscape development."

Comment: The arguments in 4.1 are interesting, but it is difficult to claim the advantages of the complexity method to DSM. These are the two phases of the approach, and the complexity analysis relies on the results of DSM. With the complexity analysis, the DSM results can be better visualized and interpreted. So, the title of 4.1 is suggested to be adjusted.
Authors: Thank you for reading carefully. Sorry for the ambiguity in the title. I will change the title to "Advantages of the combination of the Δ complexity method and DSM."

Comment: In Section 4.2, the authors attribute heterogeneity to "tree throw" and "human activities."This is speculative. How do you know it is tree throw and not tillage? Or bioturbation by small mammals? Broaden the discussion of mechanisms. If you cannot prove it is tree throw, refer to it generally as "bioturbation" or "pedoturbation." Compare your findings with other studies in APTZ zones that have identified specific erosion drivers.
Authors: We appreciate the reviewer's careful reading. Relevant literature (Li et al. 2016; Zhang and Liu, 2018) indicates that tree throw is a frequent occurrence under the topographic and soil conditions of the Bashang region. Accordingly, tree throw can be regarded as the dominant driver of pedoturbation in this area. Furthermore, we have conducted comprehensive and detailed field surveys across the study area, which has granted us an in-depth understanding of local conditions. Based on these field observations, we confirm tree throw indeed occupies a dominant position in

pedoturbation.

Comment: Regarding the topic of landscape evolution, the approach of this study seems to be effective for landscape scale issues. Can author give any prospect about the significance of this approach to larger scale soil mapping?

Authors: We appreciate the reviewer's careful reading and insightful thoughts. Yes, this method is effective at the landscape scale. Applying it at the landscape scale using catchments as the analytical unit can help us understand the patterns of soil formation at that scale and identify sensitive areas. It also enables us understand the soil of a region from a mechanistic perspective. At the national scale, using a province as the analytical unit would lack clear physical meaning. However, we can select typical landscapes within different regions to apply the △complexity method, thereby revealing the mechanisms of soil landscape evolution under varying environmental conditions. We will make sure to incorporate further discussion on this aspect in the Discussion section.

Comment: Determination of soil complexity requires a certain area or a group of mapping grids. Catchment was chosen for the unit of calculating the complexity, is there any other possibility of selecting spatial unit for the complexity? For example, how to determine the complexity in flat landscapes? Such issue can be considered in the Discussion.

Authors: We appreciate your valuable reminder. You are absolutely correct that delineating analysis units based on catchments is meaningful for landscapes with prominent topographic relief. How to partition regions in flat landscapes is indeed a question well worth considering. I believe that in flat areas, fixed-size regular grids (e.g., 500 m*500 m or 2 km*2 km) or complete land-use patches could serve as viable computational units. I will incorporate this aspect of thinking into the Discussion

Comment: In both the Abstract and Conclusion, authors present the values of the changes of the complexity, but it is not clear what do these numbers mean and what information readers can get.

Authors: We appreciate the reviewer's careful reading. Since △complexity represents the difference between complexity values of two soil layers within the same catchment, its magnitude varies with the size and order of magnitude of different data properties. The exact value of this metric is not our primary concern. In this study, we therefore focus primarily on the sign (positive or negative) of the △complexity values to determine the direction of change in soil properties between layers. Afterwards, I will add the proportion of positive and negative areas after the specific values to indicate the proportion of convergent and divergent catchment areas within the region, making the discussion more specific. This will make the discussion more concrete and informative. For example, change to "The Δcomplexity of PSD spans from -0.089 to 0.042 % cm^{-1} for both deep and shallow layers, with 36% area divergence and 64% area convergence in the shallow layer, 78% area divergence and 22% area convergence in the deep layer. Whereas that of MS ranges from -0.6 to 0.96 10^{-8} m^3 kg^{-1} cm^{-1}, with 67% of the shallow area showing divergence and 33% showing convergence, while 71% of the deep area exhibited divergence and 29% exhibited convergence."

Comment: The information of the soil types is missing in 2.1, which is quite a pity especially

when the soil is the topic of the study. More introduction about the soil characteristics would help readers understand the whole results.
Authors: We will add descriptions of soil types in Section 2.1. The zonal soil typical of the study area is chestnut soil.

Comment: The language of the manuscript is basically good, but it can be refined to make the manuscript easier to be read. Some expression should be improved. For example, In 2.3, "Clay is an important property …" is not so accurate, it should be the clay content. There are still some mistakes in the manuscript, for example, in Line 125, the reference is missing.
Authors: We appreciate the reviewer's careful reading. We will continue to improve the language and references in the manuscript. Section 2.3 will change to clay content.

Minor comments:

Comment: Line 18: % cm-1->"% per cm"
Authors: It will be changed to "% per cm".

Comment: Line 30: "Soil is a four-dimensional natural body" -> Consider a more direct opening
Authors: We will rewrite this sentence. It will be changed to "Soil is inherently four-dimensional: length, width, depth, and age, whose properties are variable in space and time due to differences in the soil forming factors."

Comment: Line 57: "evolutionary pathways of Van der Meij (2022)" -> Ensure you clearly distinguish between Van der Meij's temporal model and your spatial adaptation.
Authors: We will further distinguish between Van der Meij's temporal model and my spatial adaptation.

Comment: Line 145: define window size for the equation 5
Authors: Thank you for your reminder. Equation 5 is calculated based on the catchment area, with an area range of "1-4.9 km^2". We will add this information in the methods section.

Comment: Table 2: Ensure units for RMSE are clear
Authors: Thank you for your reminding. RMSE has units that are consistent with the units of the original data. We will add RMSE units to Table 2.

Comment: Line 270: "DSM... lacks of quantification" -> "Lacks quantification" of what?
Authors: Sorry for not specifying what quantification DSM lacks. We will provide additional clarification on this part. The quantification is a process of calculating the standard deviation of soil properties using catchments as the analytical units, which is called complexity. This takes into account the degree of dispersion in soil property data distribution with the same catchment in the same layer. The difference between two layers divided by the depth interval is Δ complexity, and the positive or negative value of Δ complexity indicates the direction of change in soil property data across different layers within the same catchment. This differs from previous digital soil mapping that focused solely on grid cell values.

References mentioned in this review that are not already in the manuscript's reference list:

Li Y, Liu L, Feng K, et al. Spatial distribution characteristics and wind breakage rules of debarked birch in northern Yanshan Mountains[J]. Scientia Silvae Sinicae, 2016, 52(1): 10-17. (in Chinese with English abstract)

Zhang K, Liu J. Development and Application of the Shelter Forest Health Evaluation Index System in Bashang Region of Hebei[J]. 2018.