

## Review: “GTDI: a gaming integrated drought index implying hazard causing and bearing impacts changing” by Zhao et al.

RC1: 'Comment on nhess-2024-45', Anonymous Referee #1

The study proposes an integrated drought index (GTDI) that combines hazard-causing (SPEI) and hazard-bearing (SSMI) indices using game theory. The GTDI is compared with an entropy-based index (ETDI) and validated against LAI data in the Wei River Basin. The key findings are that GTDI outperforms single indices and ETDI in identifying droughts spatiotemporally, and can monitor changes in hazard-causing vs bearing impacts. Overall, the manuscript is well-written and the methodology appears sound. I have a few suggestions for improvement:

We greatly appreciate the positive feedback. We would like to express our gratitude for your valuable comments and suggestions. We are grateful for the acknowledgement of the work. We would like to assure the reviewer that we will carefully address all concerns and incorporate the suggestions into an improved version of the manuscript. We are committed to enhancing the quality of our manuscript based on the reviewers' comments.

### Major suggestion:

1. The novelty and significance of the GTDI should be highlighted more clearly in the Introduction. Discuss how it advances integrated drought indices beyond existing approaches like copula functions and entropy weighting. Articulate the unique advantages of using game theory.

**Answer 1:** We greatly appreciate the positive evaluation for this study. Indeed, we strongly agree with your opinion that emphasizing the unique advantages of using game theory will contribute to the enhancement of our manuscript. We will further highlight the advantages of game theory methods in the revised manuscript. For example:

*“Therefore, game theory is suggested for the integration of drought indices because it can comprehensively consider the opinions of each party to achieve a distribution pattern that satisfies each participant [1,2], which is superior to the entropy weight method in weight allocation, and its calculation process is simpler than copula functions.”*

- [1] Lai, C., Chen, X., Chen, X., Chen, X., Wang, Z., Wu, X., and Zhao, S.: A fuzzy comprehensive evaluation model for flood risk based on the combination weight of game theory, *Nat. Hazards.*, 77, 1243-1259, <https://doi.org/10.1007/s11069-015-1645-6>, 2015.
- [2] Jato-Espino, D. and Ruiz-Puente, C.: Bringing Facilitated Industrial Symbiosis and Game Theory together to strengthen waste exchange in industrial parks, *Sci. Total Environ.*, 771, 145400, <https://doi.org/10.1016/j.scitotenv.2021.145400>, 2021.

2. The authors compare the GTDI with the ETDI, showing that the GTDI is more accurate. However, additional drought indices like the Standardized Compound Event Indicator (SCEI) and Standardized Dry and Hot Index (SDHI) (Hao et al., 2018, 2019; Wu et al., 2020) are constructed using similar approaches. Comparing the GTDI with these indices would provide readers with valuable insights into its performance relative to state-of-the-art methods in the field.

**Answer 2:** We greatly appreciate the positive feedback for this study. We have carefully read the three references you provided and gained very useful inspiration. Thank you very much for providing us with valuable references and research ideas. Unfortunately, we found that the relevant drought indices in the references you provided mainly focus on the hot summer, which is not completely consistent with the drought period covered in this manuscript, as our research paid attention to continuous, year-round drought assessments. In any case,

your suggestions have provided us with great inspiration and thought, as well as a useful idea for our subsequent research.

3. Comment on the sensitivity of GTDI to the choice of input indices. Would the results change meaningfully if indices other than SPEI and SSMI were used? Some discussion of generalizability would be useful.

**Answer 3:** Thank you for pointing out this issue. In this study, game theory is a linear combination method that uses the data characteristics of both parties to find the optimal combination. Therefore, when the object of the game changes, such as using drought indices other than SPEI and SSMI, the weight allocation between the two parties will inevitably change accordingly, resulting in different calculation results of the integrated drought index. Your perspectives are really valuable and forward-looking, and what you point out is also ongoing work in our other related research.

4. The conclusion section could be more concise, focusing on the key findings and their implications.

**Answer 4:** Thank you for highlighting shortcomings in our manuscript. We will proceed as suggested and further condense the conclusion section to highlight the main findings and points.

**Minor suggestions:**

(Line 21-22) Include a brief description of the assessment method in the abstract.

**Answer:** Thank you very much for your comment. We apologize for the inappropriate wording. In fact, there is no assessment method here. Our "assessment" actually refers to comparing the temporal and spatial development trajectory of droughts identified by GTDI with SPEI and SSMI. The use of this word may have caused your misunderstanding. Therefore, we intend to modify this sentence as follows:

*"Furthermore, a comparative analysis is conducted on the temporal trajectories and spatial evolution of droughts identified by GTDI with SPEI and SSMI to discuss the GTDI's advancedness in monitoring changes in hazard-causing and bearing impacts."*

(Line 24-25) Explain concisely in the abstract why the ETDI was used as a benchmark to demonstrate the GTDI's efficiency.

**Answer:** Thank you for this comment. The integrated drought index proposed in this paper is constructed based on the game theory method, while ETDI is constructed based on the entropy theory. Both methods belong to linear combination methods, and the entropy theory has been applied to the development of integrated drought indices [3]. Therefore, the comparison between ETDI and GTDI is helpful to reflect the characteristics of GTDI. To address your suggestion more comprehensively, we will briefly explain the reasons for using ETDI as a comparison for GTDI in the abstract. For example:

*"Also, the entropy theory-based drought index (ETDI) is induced to incorporate a spatial comparison to the GTDI to illustrate the rationality of gaming weight integration, as both entropy theory and game theory belong to linear combination methods in the development of the integrated drought index, and entropy theory has been applied in related research [3]."*

- [3] Huang, S., Chang, J., Leng, G., and Huang, Q. Integrated index for drought assessment based on variable fuzzy set theory: a case study in the Yellow River basin, China, *J. Hydrol.*, 527, 608-618, <https://doi.org/10.1016/j.jhydrol.2015.05.032>, 2015.

(Line 58-70) Consider condensing this paragraph to improve the paper's focus.

**Answer:** Thank you for your suggestion. We will improve this paragraph in the revised manuscript as suggested. For example:

*“Drought is currently categorized into four types based on distinct description objects: meteorological, agricultural, hydrological, and socioeconomic droughts [4,5]. Despite differing definitions and emphasis, meteorological drought is always regarded as the root cause of the other three types of drought [6]. In terms of the driving mechanism of drought occurrences, meteorological drought indicates the causative attribute of drought [7], whereas the other three primarily reflect the state of hazard-bearing entities. Concurrently examining the hazard-causing and hazard-bearing components of drought is essential for effective estimation and management of drought risk.”*

[4] Wilhite, D.A., and Glantz, M.H.: Understanding: the drought phenomenon: the role of definitions, *Water Int.*, 10, 111-120, 1985.

[5] Shah, D., and Mishra, V.: Integrated Drought Index (IDI) for drought monitoring and assessment in India, *Water Resour. Res.*, 56, e2019WR026284, <https://doi.org/10.1029/2019WR026284>, 2020.

[6] Ma, B., Zhang, B., Jia, L., and Huang, H.: Conditional distribution selection for SPEI-daily and its revealed meteorological drought characteristics in China from 1961 to 2017, *Atmos. Res.*, 246, 105108, <https://doi.org/10.1016/j.atmosres.2020.105108>, 2020.

[7] Zhang, J., Wang, J., Chen, S., Wang, M., Tang, S., and Zhao, W.: Integrated Risk Assessment of Agricultural Drought Disasters in the Major Grain-Producing Areas of Jilin Province, China, *Land.*, 12, 160, <https://doi.org/10.3390/land12010160>, 2023.

(Line 76-78) Rephrase this sentence for clarity.

**Answer:** We apologize for the lack of clarity. Your suggestions are valuable for improving this manuscript. As we all know, drought events have complex causes and a wide range of impacts. A single type of drought index is often insufficient in scientifically describing the spatiotemporal evolution characteristics of droughts [8], and is insufficient to fully and objectively explain the extensiveness of the impact of drought events and the complexity of their formation [9]. Therefore, many scholars are committed to developing a comprehensive drought index from multiple dimensions. Therefore, we will rephrase this sentence as follows:

*“However, due to the complex causes and wide-ranging impacts of drought events, a single type drought index usually cannot fully and effectively reflect the spatiotemporal development process of drought events [8-9]. As a result, much effort has been expended in developing comprehensive drought indices, such as .....”*

[8] Chang, J., Li, Y., Wang, Y., and Yuan, M.: Copula-based drought risk assessment combined with an integrated index in the Wei River Basin, China, *J. Hydrol.*, 540, 824-834, <https://doi.org/10.1016/j.jhydrol.2016.06.064>, 2016.

[9] Wei, H., Liu, X., Hua, W., Zhang, W., Ji, C., and Han, S.: Copula-Based Joint Drought Index Using Precipitation, NDVI, and Runoff and Its Application in the Yangtze River Basin, China, *Remote Sens.*, 15, 4484, <https://doi.org/10.3390/rs15184484>, 2023.

(Line 80-81) Elaborate on why the mentioned indices struggle to distinguish between meteorological and agricultural drought influences and evaluate changes in regional patterns.

**Answer:** Thank you for this comment. The Palmer Drought Severity Index, also known as the mentioned drought index, is a drought index based on the relationship between water supply and demand [10]. Its calculation involves multiple variables such as precipitation, temperature, and soil moisture [11]. Therefore, it is difficult for us to understand the dynamic relationship between its multiple components based on this drought index alone. That is, when a drought event occurs, we cannot directly understand through PDSI whether the drought is caused by meteorological factors (precipitation shortage) or agricultural factors (soil moisture deficit). At the same time, since the dominant factors causing drought in different regions may not be consistent, it is even more difficult to obtain the spatial distribution of drought inducements using the PDSI calculated based on the relationship between water supply and demand.

[10] Palmer, W.C.: Meteorological drought, US Department of Commerce, Weather Bureau, Washington, DC, 1965.

[11] Yan, H., Wang, S. Q., Wang, J. B., Lu, H. Q., Guo, A. H., Zhu, Z. C., and Shugart, H. H. (2016). Assessing spatiotemporal variation of drought in China and its impact on agriculture during 1982–2011 by using PDSI indices and agriculture drought survey data. *Journal of Geophysical Research: Atmospheres*, 121(5), 2283-2298.

(Line 89-91) Copulas are an efficient tool for constructing drought indices, and the samples do not necessarily need to follow a specific probability density function. For example, empirical probability functions can effectively fit the samples. Consider modifying this paragraph accordingly.

**Answer:** Thank you for pointing out this issue, which contributes to the enhancement of our manuscript. We would like to express our sincere gratitude for pointing out the inappropriateness in the manuscript. We will choose our words carefully and modify this paragraph as follows:

*“It should be noted that copula functions are possibly reliant on the assumption that samples follow a specific probability density function [12]. However, due to the complicated interactions between the atmosphere, vegetation, soil, and groundwater, the drought does not generally meet it.”*

[12] Zhang, Y., Huang, S., Huang, Q., Leng, G., Wang, H., and Wang, L.: Assessment of drought evolution characteristics based on a nonparametric and trivariate integrated drought index, *J. Hydrol.*, 579, 124230, <https://doi.org/10.1016/j.jhydrol.2019.124230>, 2019.

(Line 136-137) Provide a rationale for using soil moisture data from the 0 to 10 cm surface layer, as agricultural drought indices often utilize soil moisture data from the root zone.

**Answer:** Thank you for this comment. The soil surface layer of 0 to 10 cm has a great impact on crop growth and can accurately reflect agricultural drought conditions [13]. In addition, there are many related studies using soil moisture data from 0 to 10 cm of the soil surface for agricultural drought assessment [14,15], and effective drought assessment results have been achieved. Therefore, we used soil moisture data from 0 to 10 cm to calculate the agricultural drought index SSMI in this study.

[13] Souza, A. G. S. S., Neto, A. R., and de Souza, L. L. (2021). Soil moisture-based index for agricultural drought assessment: SMADI application in Pernambuco State-Brazil. *Remote Sensing of Environment*, 252, 112124.

[14] Zhou, K., Li, J., Zhang, T., and Kang, A. (2021). The use of combined soil moisture data to characterize agricultural drought conditions and the relationship among different drought types in China. *Agricultural Water Management*, 243, 106479.

[15] Baik, J., Zohaib, M., Kim, U., Aadil, M., and Choi, M. (2019). Agricultural drought assessment based on multiple soil moisture products. *Journal of arid environments*, 167, 43-55.

(Line 140-141) Include details on the resampling method used.

**Answer:** Thank you for your suggestion. This study employs the bilinear interpolation method for resampling. According to your reminder, we will modify this sentence as follows:

*“Additionally, in order to facilitate calculation and analysis, precipitation, air temperature, soil moisture, and leaf area index (LAI) data were all resampled to the same spatial resolution of 0.125° using the bilinear interpolation method in this study.”*

(Line 153-154) Explain the reasoning behind using SPEI-3 and SSMI-3.

**Answer:** Thank you for pointing out this issue. Drought indices at different time scales can reflect the dry and wet conditions of the study area at different time periods in the past. The 3-month drought index can reflect short- and medium-term dry and wet conditions and is more sensitive to seasonal drought, which helps us identify and analyze seasonal drought in the Wei River Basin. So, we used SPEI-3 and SSMI-3 to construct an integrated drought index GTDI with a three-month scale in this study.

(Line 206) Add a reference to support the statement.

**Answer:** Thank you for your suggestion. We will add a reference for the correlation levels of PCC as follows:

*“Table 3. The absolute value range of PCC and correlation levels [16].”*

[16] Yang, Y., and He, Y. (2022). A fault identification method based on an ensemble deep neural network and a correlation coefficient. *Soft Computing*, 26(18), 9199-9214.

(Line 246) Incorporate a duration threshold in the drought identification criteria.

**Answer:** Thank you for your positive feedback. It should be pointed out that the drought identification method we used, that is, a spatiotemporal continuity technique [17], is inconsistent with the research route of using drought duration to identify drought events. In the drought identification process of this study, as long as the drought index value at a grid point is lower than the drought index threshold of -1, we determine it as a drought grid point. When the total area of drought grid points in a certain month exceeds the drought area threshold, we determine that month as a drought month. Furthermore, when multiple consecutive months are determined to be drought months, if the overlapping area of drought areas in space between two adjacent consecutive drought months exceeds the drought area threshold, we determine that these two months belong to the same drought event, otherwise, they belong to different drought events. Since we are studying drought conditions at the monthly scale, the minimum drought duration of the drought event we identified is one month. Therefore, we have no way to add a drought duration threshold that does not match our drought event determination method here. But anyway, thank you very much for your valuable suggestions.

[17] Deng, C.L., She, D.X., Zhang, L.P., Zhang, Q., Liu, X., and Wang, S.X.: Characteristics of drought events using three-dimensional graph connectedness recognition method in the Yangtze River Basin, China, *Trans. Chin. Soc. Agric. Eng.*, 37, 131-139, 2021.

We express our gratitude for your valuable input, and we assure you that all of your comments and concerns will be carefully considered and incorporated into the revised manuscript.