Response to the anonymous reviewer's comments

Anonymous referee #1:

Zhao et al. mapped a new (2019 to 2020) gridded (0.5° × 0.5° resolution) rice calendar for monsoon Asia based on Sentinel-1 and Sentinel-2 satellite images for monitoring the rice transplanting date, harvest date, and number of rice croppings. Its result may reveal the rice phenological dates for three croppings in monsoon Asia. However, three major points needed to be improved.

We greatly appreciate the valuable and constructive comments provided by the reviewer. In the following responses, we will adress each comment point-by-point. The responses to the comments are presented in blue font, and changes to the manuscript are highlighted in red with a grey background.

#1 The authors use two steps to map the rice calendar: (1) detection of rice phenological dates and number of rice croppings through combination of a feature-based algorithm and the fitted Weibull function, and (2) spatio-temporal integration of the detected transplanting and harvest dates using von Mises maximum likelihood estimates. However, there is no logical relationship between the two steps. In its current version, it seems that the authors use two different methods (combination of a feature-based algorithm and the fitted Weibull function, and von Mises maximum likelihood estimates) to monitor the rice phenological dates, but did not compare the advantages and disadvantages of the two methods. Maybe the output from step one would be the input to step two? The authors should explain the logical relationship, because this is the key of this study.

Response: We extend our sincere appreciation to the reviewer for the valuable feedback. As you rightly pointed out, the output from step one would serve as the input for step two. In Step 1, we utilized a feature-based algorithm to extract the transplanting and harvest date (as detailed described in Lines 181-205). To identify the number of rice croppings, a fitted Weibull function was employed (as detailed described in Lines 207-226). Upon completing Step 1, we successfully detected all the transplanting and harvest dates across two years for each grid. However, it is important to note that these detected transplanting and harvest dates within each grid can vary annually due to different weather conditions, the impact of climate change, adjustments in agricultural schedules, and the availability of satellite images. Furthermore, the transplanting and harvest dates for a specific cropping season in one grid can significantly differ from those in neighboring grids, possibly indicating detection errors. Therefore, the spatio-temporal integration of these detected transplanting and harvest dates, referred to as Step 2, is a necessary process for generating a multi-year spatially averaged rice calendar. In response to your suggestion, we have revised the 2.3.2 Section to emphasize the key points that Step 1 is the input of Step 2. The revised contents are as follows:

- All the transplanting and harvest dates across two years for each grid were detected in Step 1 by using the algorithms and processes described above. However, these detected transplanting and harvest dates in each grid vary annually due to different weather conditions, the effects of climate change, adjustments in agricultural schedule, and the availability of satellite images. Additionally, the detected transplanting and harvest dates for a specific cropping season in a grid can differ markedly from those in neighboring grids, possibly indicating detection errors. Therefore, the temporal and spatial integration of the detected transplanting and harvest dates, referred to as Step 2, is a necessary step for generation of a multi-year, spatially averaged rice calendar (Lines 237-242).

We have made a revision that makes the logical relationship between Step 1 and Step 2 more clear in the Abstract:

- The methodological framework incorporates two steps: (1) detection of rice phenological dates and number of rice croppings through combination of a feature-based algorithm and the fitted Weibull function, and (2) spatio-temporal integration of the detected transplanting and harvest dates derived from step 1 using von Mises maximum likelihood estimates (Lines 18-21).

At the same time, we have added arrows in Figure 2 to show that the transplanting and harvest dates obtained in Step 1 are the inputs for Step 2. Correspondingly, its description and caption have also been revised as follows:

- The overall methodology for rice calendar mapping, which is summarized in Fig. 2, can be divided into two steps. The first step is extraction of transplanting and harvest dates and detection of the number of rice croppings, depicted in Fig. 2 Step 1.~~-1 as the algorithm for phenological dates and number of rice croppings detection and in Fig. 2 Step 1-2 as the process of phenological dates and number of rice croppings detection.~~ The transplanting and harvest dates obtained in the first step (Step 1) require temporal and spatial integration for the generation of the rice calendar (Fig. 2 Step 2). The following sections provide elaboration on the major procedures involved in each step (Lines 168-173).

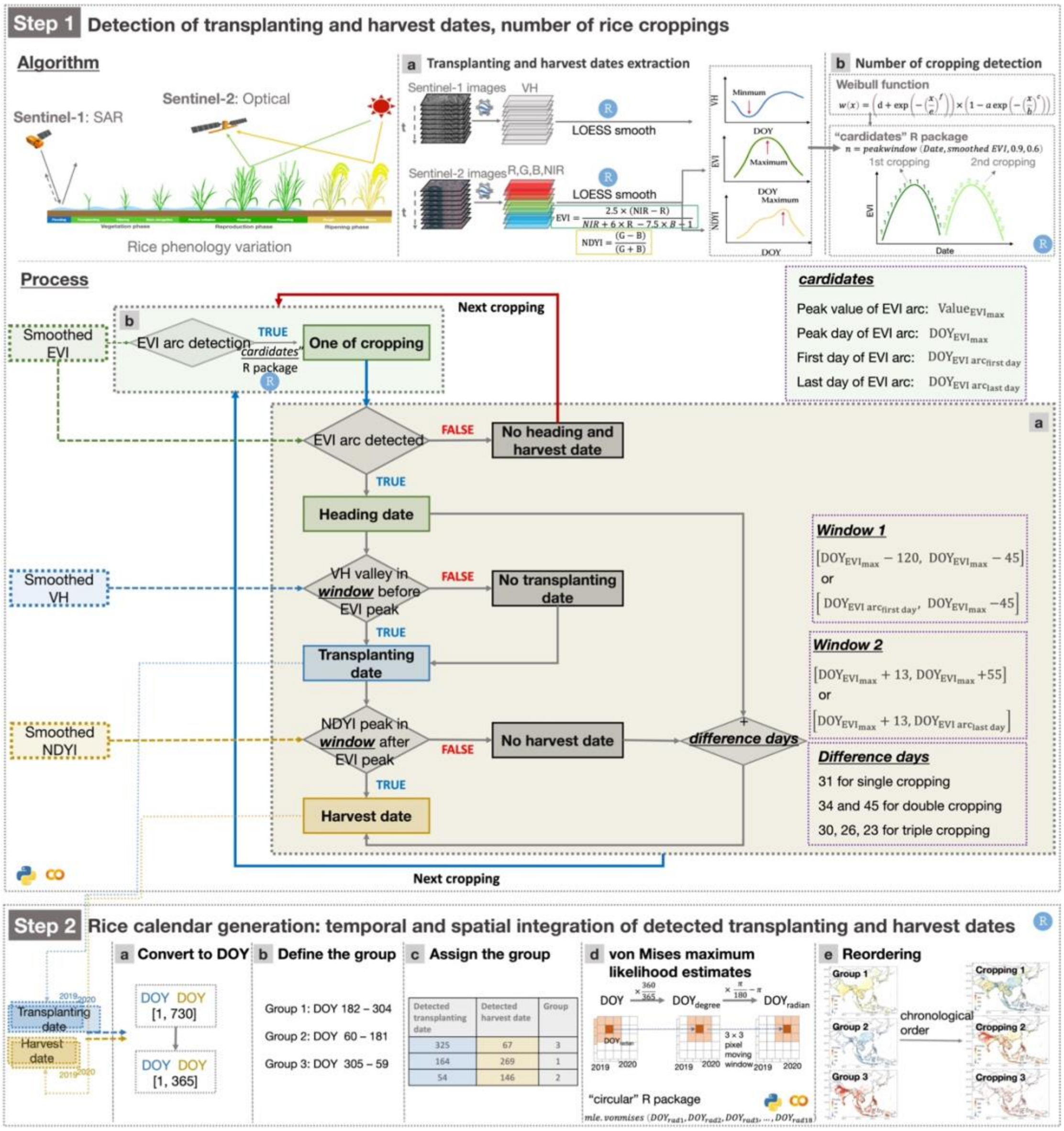

Figure 2 Workflow for gridded rice calendar mapping based on satellite images. Step 1 depicts the algorithm and process of transplanting and harvest dates extraction, along with the detection of number of rice croppings, as shown in the first box. In Step 2, the generation of the rice calendar is described, relying on the detected transplanting and harvest dates derived from Step 1, through the temporal and spatial integration of the detected phenological dates displayed in the second box (Page 8).

Moreover, we have improved the paragraph that emphasizes the derivation of Step 2 from Step 1 in the Results and Discussion section:

- Temporal and spatial integration of detected transplanting and harvest dates, as derived from Step 1, pose a great challenge owing to flexible agricultural schedules, and the availability of satellite imagery (Lines 454-455).

#2 The validation of the accuracy of the results is weak and scarce. The authors only compare the identified rice phenological dates with the existing products, including the RiceAtlas rice calendar, the RICA rice calendar, and the SAGE rice calendar, instead of field observation of rice phenology. It is inappropriate because the existing products themselves have identification errors, thus lacking of reliability. Therefore, it is meaningless to verify the detection results using the biased information. The authors should add the contents about verifying the results with actual field observations of rice phenology.

Response: We sincerely thank the reviewer for the valuable comment. We acknowledge the critical role of rice calendar accuracy in validating the precision of our proposed rice calendar. We completely understand the review's concerns about the accuracy of existing rice calendars, which may contain the uncertainties due to several reasons. It is worth noting that we have addressed this issue in detail in the "3.4 Accuracy of reference rice calendars" section of the original version, as follows:

"*Accuracy of reference rice calendar*. Although the proposed rice calendar showed reasonable performance in comparison with that of the other rice calendars, it should consider the accuracy of the reference rice calendars. In particular, when evaluating transplanting and harvest dates against the RiceAtlas rice calendar, it is worth noting that the phenological dates were sources from census data, database, publications, and report compilations (Laborte et al., 2017). Another concern regarding the RiceAtlas rice calendar is the overlay of phenological dates between rice cropping seasons. Additionally, the RiceAtlas, RICA, and SAGE rice calendars are based on the administrative scale, resulting in large spatial coverage with only one recorded phenological date and number of rice croppings (Fig. S5-S7). It should also be mentioned that some rice calendars, e.g., SAGE, are poorly documented and do not record triple croppings (Scaks et al., 2010) (Lines 494-501)."

Regarding RiceAtlas, despite the presence of detection errors, it remains the only detailed global rice calendar to date (Laborte et al., 2017). Since its publication in 2017, RiceAtlas rice calendar has been cited 84 times (according to Web of Science). It stands as the widely accepted rice calendar extensively used in numerous research domains, including rice calendar validation (e.g., RICA rice calendar in Mishra et al. (2021), Iizumi et al. (2019)), mapping rice paddy field distribution (Han et al., 2021; Luintel, et al., 2021), predicting rice production (Oort et al., 2017; Wu et al., 2023), and estimating methane emissions (Crippa et al., 2020; Ouyang et al., 2023). In fact, researchers regard RiceAtlas as the standard database for comparing rice phenology based on earth observation (Mishra et al., 2021).

Our primary objective here is to compare the differences among similar large-scale rice calendar products. The improved accuracy of our proposed rice calendar, which outperformed the RICA rice calendar when compared with RiceAtlas rice calendar, highlights the critical importance and necessity of our proposed rice calendar. Our proposed rice calendar can integrate the strengths, such as consistent detection through remote sensing methods as seen in the RICA rice calendar, while addressing the weaknesses, such as the coarse spatial resolution found in existing large-scale rice calendars like RiceAtlas and RICA rice calendars and limited number of rice cropping seasons in the SAGE rice calendar). This effort has resulted in the development of our new, relatively finer rice calendar.

As reviewer rightly point out, actual field observations are essential for validating the accuracy of rice phenology detection methods. Fortunately, we have previously validated the rice phenology detection methods (feature-based algorithm) used in this rice calendar production in a prior study using actual field observations (Zhao et al., 2023). Results revealed a bias of 4 and -13 days for transplanting and harvest dates, respectively (as shown in Fig. 6, Fig. 7, Table 1, and Appendix A in Zhao et al. (2023)). Moreover, we employed various spatial scales, including actual site observations, sub-national, and 0.5° gridcell scales, to rigorously validate our feature-based algorithm, ensuring its robustness (Zhao et al., 2023). We have added this description in the revised manuscript as follows:

- A feature-based algorithm has been proposed for rice phenology detection at the large scale (Zhao et al., 2023). The superiority of this algorithm lies in the use of backscattering (VH) and vegetation indices (Enhanced Vegetation Index (EVI) and Normalized Yellow Index (NDYI)) derived from Sentinel-1 and Sentinel-2 images, which reflect features related to rice cultivation such as flooding, maximum leaf area, and most yellowness around transplanting, heading, and harvest date. Additionally, this algorithm has successfully tracked rice phenological dates in different cropping systems (single, double, and triple croppings) and at different spatial scales (sub-nation, 0.5° gridcell, and site scales) (Zhao et al., 2023). Thus, the recognition of rice phenological dates is based on the feature-based algorithm (Lines 79-85).
- The feature-based algorithm was used on the smoothed VH, EVI, and NDYI time series data to capture the aforementioned phenological characteristics of rice crops (Zhao et al., 2023). This algorithm's robustness has been confirmed at multiple spatial scales (sub-nation, 0.5° gridcell, and site scales) and cropping systems (single, double, and triple croppings) in monsoon Asia (Zhao et al., 2023). The transplanting date was determined by identifying the minimum VH intensity from the shortest plants above the water surface. As ~~the~~ rice plants grow above the water surface and interact with the incident radar signal, the VH intensity gradually increases (Torres et al., 2012). The harvest date was detected using the yellow signal derived from the NDYI, which employs a combination of green and blue bands to represent the balance between rice growth and senescence. Consequently, the NDYI value reaches a peak (approaches nearly 0 from negative values),

indicating the maximum yellowness associated with the harvest date (Zhao et al., 2023) (Fig. 2 Step 1 Algorithm a) (Lines 187-193).

In summary, our proposed rice calendar has undergone validation using other rice calendar products as well as through field observations of rice phenology. We hope this addresses your concerns adequately.

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#3 The authors emphasize for many times that the proposed rice calendar fills the gaps in high resolution rice calendars, like Line 27, and Line 96 (high spatial resolution, 0.5°). However, there are currently so many high resolution satellites images, like Landsat images for 30 m and Sentinel-1/2 satellite images for 10 m. The spatial resolution for 0.5° of the proposed rice calendar cannot be called high resolution.

Response: We appreciate the constructive feedback provided by the reviewer and have incorporated this suggestion into revised manuscript. As you noted, it is indeed true that our proposed rice calendar, with a spatial resolution of 0.5°, may not be categorized as "high resolution" when compared to the 30 m or even 10 m high-resolution satellite images. It is also important to convey the advantage of our proposed rice calendar – our spatial resolution surpasses that of existing large-scale rice calendars, which are typically produced at administrative scale ranging from country to sub-country levels. Taking into account these two key aspects, we have refrained from using the term "high spatial resolution (0.5°)" and have also decided to quit using "finer-resolution rice calendar" in the revised manuscript.

The revised contents are specifically as follows:

- This novel gridded rice calendar fills the gaps in half-degree rice calendars across major global rice production areas, facilitating research on rice phenology that is relevant to the climate change (Lines 27-28).
- The objective of this study was to develop a new gridded rice calendar that highlights the following features: (a) consistent detection using remote-sensing methods, (b) spatial resolution (0.5° × 0.5°), (c) large-scale coverage (monsoon Asia), and (d) ability to extract multiple rice croppings (Lines 95-97).
- The advantages of the above-mentioned algorithms (Fig 2 Step 1, Step 2) largely contribute to the production of a gridded rice calendar. ~~The proposed rice calendar fills the gaps in finer-scale rice calendars with continental coverage using remotes sensing methods.~~ The proposed rice calendar provides spatially explicit rice phenology with continental coverage through remote sensing methods. The major difference between our proposed rice calendar and the RICA rice calendar lies in the use of a feature-based algorithm with VH and NDYI, which allows our proposed rice calendar to theoretically estimate rice phenology more accurately. Zhao et al. (2023) demonstrated that VH can accurately capture the start of paddy water logging, and NDYI is a good indicator of rice maturity stage. Our proposed rice calendar presents a highly patchy map of rice phenological information (Figs. 6 and 10a). The 0.5° resolution of our proposed rice calendar is finer than that of other rice calendars, including RiceAtlas, RICA at sub-national scale, and SAGE derived from sub-national data. This improvement greatly reduces the bias error caused by assigning averaged rice phenology to administrative units, as rice phenology can vary considerably within large administrative units (Franch et al., 2022). Furthermore, our proposed rice calendar displays the detailed distribution of rice paddy fields (Figs. 6 and 10a), in contrast to previous rice calendars that

covered entire administrative areas, irrespective of the small proportion of rice cultivation (Figs. S5-S7 and 10b-d) (Lines 466-474).

- Given the absence of an updated global/continental-scale rice calendar that can explicitly depict spatial gridded transplanting date and harvest date information, and the number of rice croppings, this study developed a new gridded rice calendar for monsoon Asia with spatially explicit detail of rice phenology using a new methodological framework based on Sentinel-1 and Sentinel-2 images (Lines 526-529).

Minor issues

1. *Line 129-130, the authors aggregated rice distribution map at 500 m resolution into 0.5° resolution by randomly selecting 20 rice fields to derive the average phenology. This process is unreasonable because 20 fields are not representative. It is suggested that the authors should first calculate the planting fraction for rice paddy at 0.5° resolution based on rice distribution map at 500 m resolution, derive the pixels which have a higher planting proportion like 80%, and then extracting the average phenology of above pixels.*

Response: We greatly appreciate the reviewer's constructive comments. Our apologies for the ambiguous description in the previous version. The rice paddy filed distribution map was aggregated to a gridded map with 0.5° resolution, INSTEAD OF converting the rice paddy field distribution map at 500 m resolution into 0.5° resolution by randomly selecting 20 rice fields to derive the average phenology. To avoid ambiguity, we have moved the sentence "This rice paddy field distribution map was aggregated to a gridded map with 0.5° resolution (Fig. 1b)." (originally located at the beginning of the sampling method paragraph) to the end of the paragraph describing the rice paddy field distribution map.

- The rice paddy field distribution map adopted in this study is from a 500 m resolution map produced using MODIS images (Zhang et al., 2020) (Fig. 1a). This map effectively displays the presence and distribution of rice paddy fields over monsoon Asia. The reliability of this map is substantiated by its strong correlation with existing rice paddy field maps across diverse areas (R^2 values ranging from 0.72 to 0.95) and its alignment with the area information obtained from FAOSTAT statistical data for each country (Zhang et al., 2021). ~~Additionally, this map has been used to develop a feature-based algorithm for rice phenology detection (Zhao et al., 2023).~~ In this study, this rice paddy field distribution map was aggregated into a gridded map with 0.5° resolution (Fig. 1b).

  ~~This rice paddy field distribution map was aggregated to a gridded map with 0.5° resolution (Fig. 1b).~~ Within each 0.5° grid, 20 rice paddy fields were randomly selected to derive the average rice phenology for that grid (Xiao et al., 2021; Zhao et al., 2023). This sampling method effectively minimizes errors caused by misclassification of rice paddy fields by excluding outliers that deviate from the averaged rice phenology (Zhao et al., 2023) (Lines 121-132).

In fact, we have already calculated the fraction of rice paddy fields at 0.5° resolution based on the rice distribution map at 500 m resolution in our research. Fig. 1b displays the percentage of rice paddy field in 0.5° grids. Green gradient indicates variation in the percentage coverage of rice paddy fields (Page 5).

From the provided fraction of the rice paddy field map (Fig. 1b), areas with a high proportion of rice cultivation are mainly located in the Indo-Gangetic Plain, the Yangtze Plain, the Ayeyarwady Delta region, and the Mekong Basin. If we extract the average phenology from these high proportion grids, we will miss the rice phenology in other grids across monsoon Asia. However, the objective of our research is to develop a gridded rice calendar that considers each grid individually. Indeed, the high proportion of rice paddy areas improves the accuracy of averaged rice phenology detection by enabling more precise identification of rice paddy fields. In contrast, our sampling method – randomly selecting 20 rice paddy fields – is suitable for both high and low proportion rice paddy area grids. It effectively selects the rice paddy fields, saving computation time and facilitates the implementation, while reducing the error of misclassification of rice paddy fields by excluding outliers that deviate from the averaged rice phenology (Fig. S2 in Supplementary in Zhao et al., 2023). The average rice phenology for each grid was therefore determined by the rice phenology that predominates in that grid.

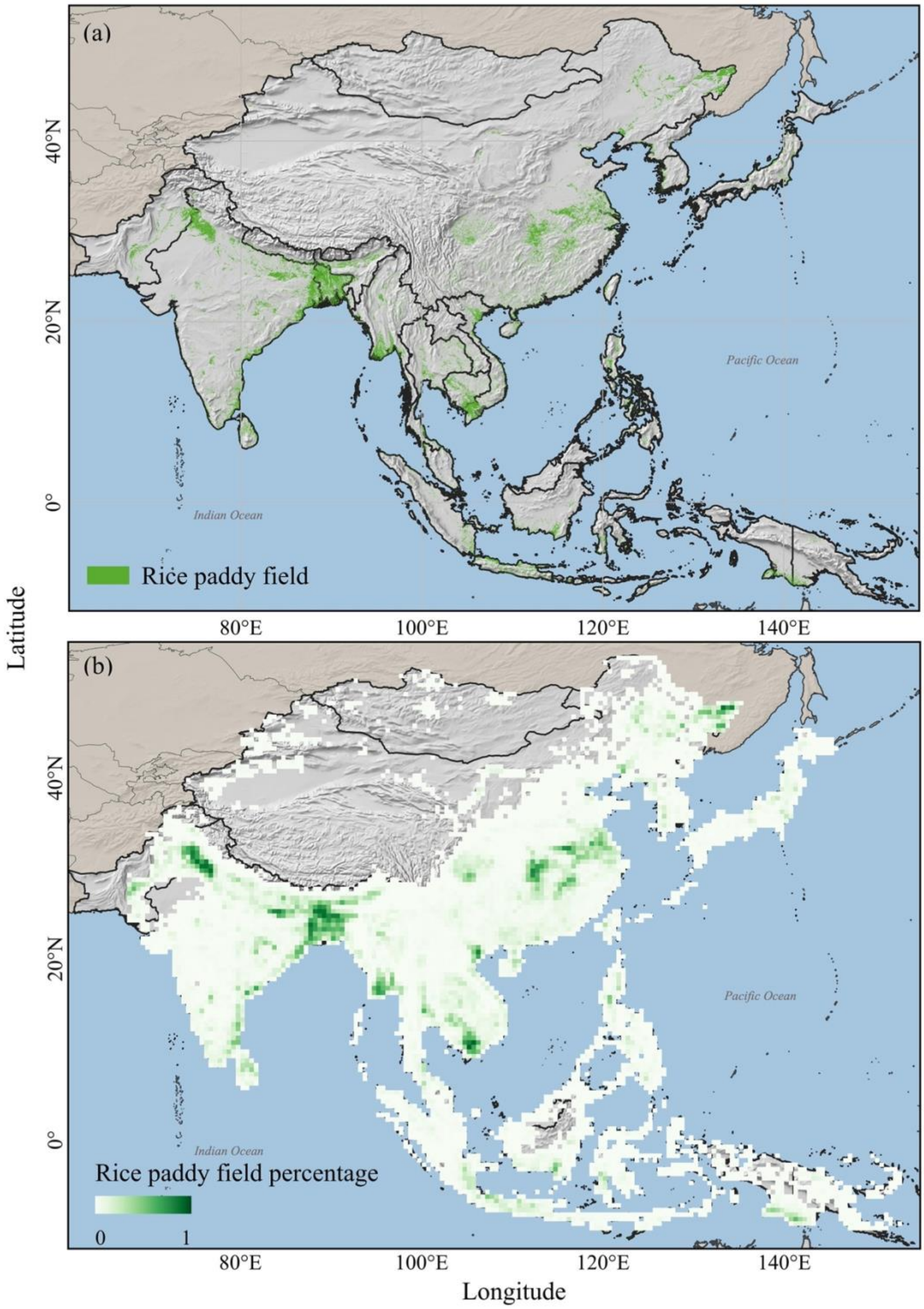

Figure 1 Location of the study area and distribution of rice paddy fields in monsoon Asia. Rice paddy field distribution map (**a**) was obtained from Zhang et al., (2020), which was produced using MODIS images. Green areas indicate rice paddy fields. Gridded rice paddy field map (**b**) shows the percentage of rice paddy field in 0.5° grids. Green gradient indicates variation in the percentage coverage of rice paddy fields (Page 5).

2. *Line 175-178, Step 1-1 and Step 1-2 describe the same thing. It is suggested that these two steps be combined.*

Response: We greatly appreciate the reviewer's suggestion. As you suggested, Step 1-1 and Step 1-2 depict the algorithms and processes for detecting rice phenological dates and number of rice croppings, respectively. Both of these sub-steps focus on the same issue: how to detect phenological dates and the number of rice croppings. Therefore, we have combined Step 1-1 and Step 1-2 into a comprehensive step, summarizing these two sub-steps as "Step 1 Detection of transplanting and harvest dates, number of rice croppings". Additionally, we have revised Figure 2 and its description to correspond to this combination.

- The overall methodology for rice calendar mapping, which is summarized in Fig. 2, can be divided into two steps. The first step is extraction of transplanting and harvest dates and detection of the number of rice croppings, depicted in Fig. 2 Step 1.~~-1 as the algorithm for phenological dates and number of rice croppings detection and in Fig. 2 Step 1-2 as the process of phenological dates and number of rice croppings detection~~. The transplanting and harvest dates obtained in the first step (Step 1) require temporal and spatial integration for the generation of the rice calendar (Fig. 2 Step 2). The following sections provide elaboration on the major procedures involved in each step (Lines 168-173).

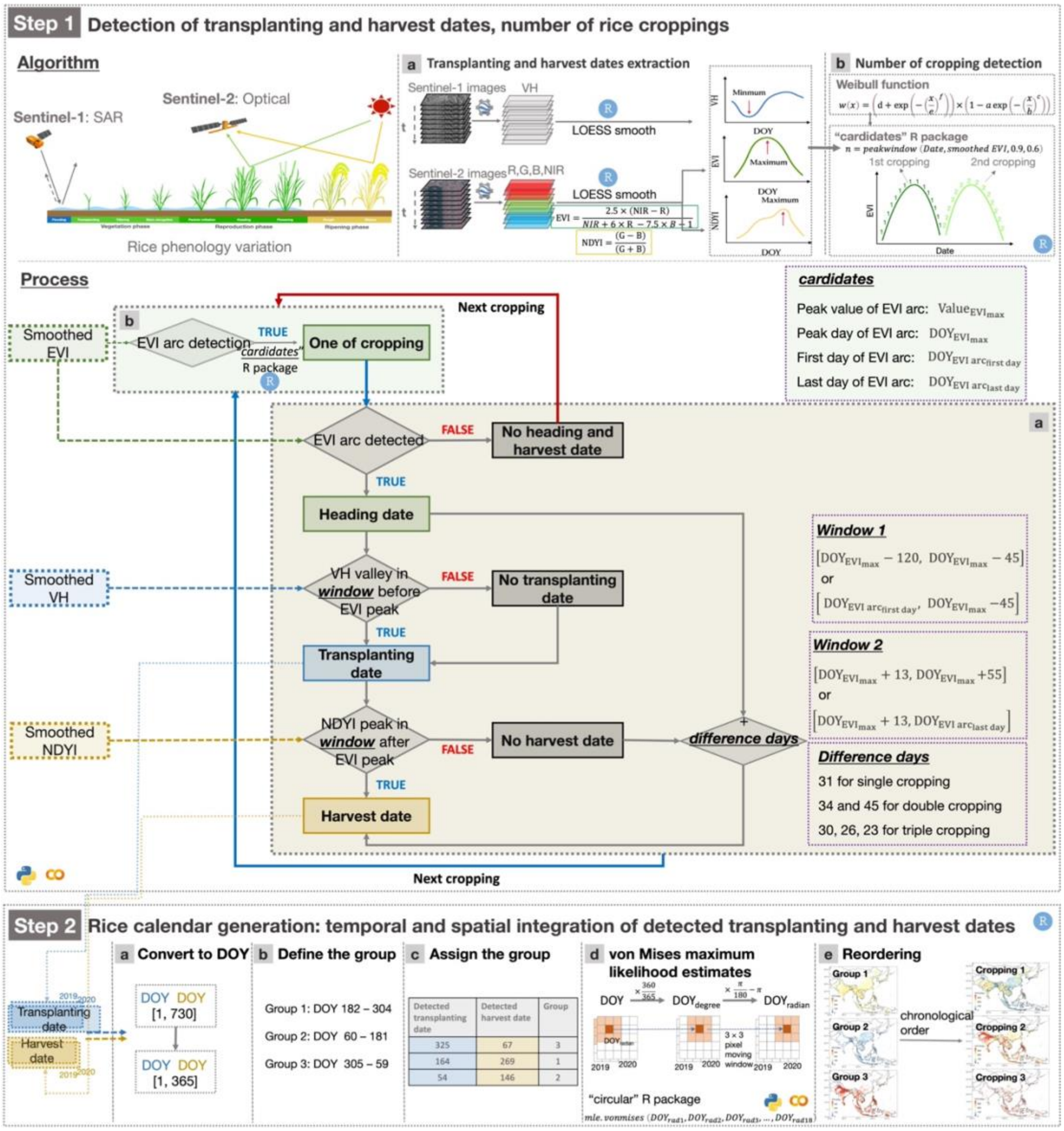

Figure 2 Workflow for gridded rice calendar mapping based on satellite images. Step 1 depicts the algorithm and process of transplanting and harvest dates extraction, along with the detection of number of rice croppings, as shown in the first box. In Step 2, the generation of the rice calendar is described, relying on the detected transplanting and harvest dates derived from Step 1, through the temporal and spatial integration of the detected phenological dates displayed in the second box (Page 8).

We have also revised the description of Step 1-1 and Step 1-2 in other contents as follows:

- **2.3.1.1 Algorithm ~~(Step 1-1a)~~ and process ~~(Step 1-2b)~~ for extraction of transplanting and harvest dates** (Line 180).
- Additionally, the time of rice harvest is characterized by irreversible yellowing of the leaves, resulting from the rapid breakdown of chlorophyll and the

photosynthetic apparatus (Zhang et al., 2021b) (Fig. 2 Step 1 Algorithm) (Lines 184-185).

- Consequently, the NDYI value reaches a peak (approaches nearly 0 from negative values), indicating the maximum yellowness associated with the harvest date (Zhao et al., 2023) (Fig. 2 Step 1 Algorithm a) (Lines 192-193).
- The minimum VH and peak NDYI were detected within the time window (Fig. 2 Step 1 Process a), indicating that only the minimum VH and the maximum NDYI values within the time window, before and after the EVI peak, can be identified as the transplanting date and harvest date, respectively (Lines 195-197).
- If the peak NDYI could not be obtained from those time windows, peak NDYI was identified using the peak EVI date ($DOY_{EVI_{max}}$) plus the corresponding difference days for each rice cropping, as referenced in Zhao et al. (2013) (Fig. 2 Step 1 Process a) (Lines 203-205).
- **2.3.1.2 Method ~~(Step 1-1b)~~ and process ~~(Step 1-2a)~~ for detecting the number of rice croppings** (Line 206).
- The six-parametric Weibull function, $w(x) = \left(\mathrm{d} + \exp\left(-\left(\frac{x}{e}\right)^f\right)\right) \times \left(1 - a\exp\left(-\left(\frac{x}{b}\right)^c\right)\right)$ (where *a*, *b*, *c*, *d*, *e*, and *f* are the free parameters to be fitted) (Rolinski et al., 2007), can be used to identify the number of rice croppings by depicting an arc with the shape of downward-opening patterns from the smoothed EVI time series (Fig. 2 Step 1 Algorithm b) (Lines 207-209).
- After application of the function (Eq. (7)), all available arcs of the smoothed EVI time series were then labelled, including the start (start day of detected EVI arc, $DOY_{EVI\ arc_{first\ day}}$), peak (peak day of detected EVI arc, $DOY_{EVI_{max}}$), and end (end day of detected EVI arc, $DOY_{EVI\ arc_{last\ day}}$) of the arc, and the peak EVI value ($Value_{EVI_{max}}$) (Fig. 2 Step 1 Process b) (Lines 219-221).
- A rice feature-based phenology algorithm (Zhao et al., 2023) was applied to Sentinel-1 and Sentinel-2 images to detect gridded rice transplanting and harvest dates (Fig. 2 Step 1 Algorithm a) (Lines 432-433).

- The fitted Weibull function, implemented in the R package (Fig. 2 Step 1 Algorithm b), automatically detects the number of rice croppings based on the shape of the smoothed EVI time series, facilitating rapid and efficient rice calendar mapping (Lines 447-448).