DATA PAPER

A detailed mangrove map of China for 2019 derived from Sentinel-1 and -2 images and Google Earth images

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Abstract
Mangroves straddle terrestrial and marine ecosystems, thus are relevant to many United Nations Sustainable Development Goals (SDG), especially to SDG-13 and SDG-14, as they are linked to blue carbon strategies and fisheries. To better achieve SDGs, China has been restoring mangroves for their ecological and societal values through strict protection and afforestation, even in areas beyond their natural northern limits. However, small fragmented mangrove patches, especially those in marginal climates, have been historically neglected by existing mangrove maps, which, because they were derived from 30-m-resolution Landsat data, are too coarse to resolve them. To overcome this problem, we applied a classification to 10-m-resolution Sentinel-1 and -2 images for 2019 and then an enhanced post-processing to identify missing mangrove patches by utilizing Google Earth images. Thus, we produced the first publicly accessible detailed mangrove map supplementing the main 10-m-resolution results with submetre data from Google Earth images. According to general quantitative evaluations, the produced map achieved an overall accuracy of 96.4 ± 0.3% based on validation data sets, an accuracy of 96.2% based on a total of 1,096 field sample plots. By evaluations in marginal climates, the produced map identified six areas with a total of seven mangrove planting areas, which is twice the number of

Dataset details
This data set contains the detailed distribution of mangroves of China for 2019. It is the most up-to-date data set for this region and derived from remote sensing-based classifications using 10-m-resolution Sentinel images and from enhanced post-processing using tidal flat constraint and Google Earth images. The focus on small patches, which largely contributes to local ecology, is a characteristic of this data set, because these patches are ignored by mangrove maps derived from coarser 30-m-resolution Landsat images and by field survey-based mangrove maps (Zhao & Qin, 2020).

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identified areas by current publicly accessible mangrove maps. The produced map also outperformed the competitors in the identification of small mangrove patches in suitable climates, and in the determination of neat and tidy boundaries of large mangrove patches. The map paid attention to these small mangrove patches because they can provide substantial ecosystem services, such as increasing the community diversity and providing habitats for local species. The map does not only serve as a basis for mangrove species mapping, leaf area index estimation and carbon stock assessment, but also improves other mangrove maps by mutual corrections.

**KEYWORDS**
fragmented mangroves, Google Earth Engine, Google Earth images, mangrove map, Sentinel

1 | INTRODUCTION

Mangroves provide a wide range of services (e.g. coastal protection from waves, breeding and nursing ground for marine species, carbon sequestration and storage) and have been closely linked to the United Nation Sustainable Development Goals (SDG), especially to SDG-13 and SDG-14 as they provide a blue carbon strategy and have a strong connection to fisheries (Carrasquilla-Henao & Juanes, 2017; Donato et al., 2011; Fakhruddin et al., 2018; Friess et al., 2019; Temmerman et al., 2013). In the context of climate change, mapping mangrove distribution not only provides a basis for estimating ecological and societal values, but also serves as a tropicalization index of the climate (Cavanaugh et al., 2019; Osland et al., 2017; Scheffel et al., 2018). Thus, the ability to provide accurate, up-to-date, detailed mangrove maps is important, especially ones that have acceptable accuracy at mangrove poleward limits.

To map mangroves, China has carried out several field investigations. According to the survey by the State Forestry Administration of China in 2001, the mangrove area in mainland China was 22,024.9 ha (Ministry of Forestry of China, 2002). In the second national survey of wetland resources, which was carried out between 2009 and 2013, the area reached 34,472.14 ha (Dan et al., 2016). In the latest survey by the National Forest and Grass Bureau, the area changed to about 29,000 ha (Wang & Hu, 2020). Considering that in the past 20 years the mangrove area of China has been increasing thanks to their strict protection (Hu et al., 2018; Jia et al., 2018; Wang et al., 2020), this area reduction may be caused by differences in investigation approaches (e.g. survey standards, experience of survey executors).

To map large-area mangroves in a cost-effective manner, approaches that combine remote sensing (RS)-based classifications with post-processing have been most common (Kuenzer et al., 2011; Purnamasayangsuksaiah et al., 2016; Wang et al., 2019a). Although there are various classification approaches have been developed, none of them guarantees reliable results before post-processing (Chen et al., 2017a; Giri et al., 2015; Zhao & Qin, 2020), because of the complexity of mangroves (e.g. the presence of different mangrove species, a large latitudinal span, and their mixing with other forest types at the fringes). Post-processing usually uses empirical thresholds (e.g. a distance to the coastline) to select classified patches that meet certain requirements (Chen et al., 2017a; Hu et al., 2018), then the selected patches are visually checked to separate them from the vegetation near water that is easily misclassified as mangroves (Chen et al., 2017a; Gao, 1998; Jia et al., 2018; Zhao & Qin, 2020).

Based on the above approaches, several mangrove maps covering China have been generated. According to the spatial resolution of the main data sources of remote sensing-based classifications, these maps can be categorized into two types: 30-m-resolution maps (i.e. mainly derived from Landsat images) and 10-m-resolution maps (i.e. mainly derived from Sentinel-1 and -2 satellite data, hereafter referred to as Sentinel). The first Landsat-based global mangrove map concentrated on mangrove distribution in the year 2000 (Giri et al., 2011). Bunting et al. (2018) mapped the global mangroves in 2010 using Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) and Landsat optical imagery. Bunting et al. (2018) also mapped global mangroves at several other time periods using the 2010 map as a baseline. However, the subset of China for 2016 from this data set (we refer to this subset map as ‘LA_Map’) estimates a mangrove area that is much smaller than that estimated from other studies, such as the mangrove map of China for 2015 by Jia et al. (2018), which was based on Landsat images at low tides with a focus on object-based image analysis (we refer to this map as ‘LT_Map’), the mangrove map of China for 2015 by Hu et al. (2018), which was based on time series of Landsat images with a focus on spectral-temporal variability metrics (we refer to this map as ‘SV_Map’), and the mangrove map of China for 2015 by Chen et al. (2017a), derived using time series of Landsat images with a focus on the phenological...
characteristics of mangroves (we refer to this map as ‘P_Map’). Due to the 30-m resolution of Landsat, mangroves in narrow strips or small fragmented patches are hard to capture with these data (Bunting et al., 2018; Hu et al., 2020; Kuenzer et al., 2011; Zhao & Qin, 2020).

Since the value of small mangrove patches has gradually been acknowledged and the availability of higher resolution data (Barbier et al., 2008; Curnick et al., 2019; Lindenmayer, 2019), 10-m-resolution mangrove maps emerged. Hu et al. (2020) migrated the spectral-temporal variability metrics to time series of Sentinel images to derive a new mangrove map of China for 2015. Zhao and Qin (2020) mapped the mangroves of China for 2017 based on time series of Sentinel with a focus on factors that affect the accuracy of mapping mangroves (namely tidal inundation, intertidal terrain, cloudiness and phenological variations of vegetation) by quantile synthesis (we refer to this map as ‘PXL_Map’). The 10-m resolution of Sentinel data provides an advantage in identifying small mangrove patches. However, some patches in Sentinel-based maps are still missing, especially those at the poleward limits of mangroves (Giri, 2016; Hickey et al., 2017; Saintilan et al., 2014).

The missing mangrove patches in Sentinel-based maps can be attributed to both classification and post-processing errors. Classification issues have been likely caused by the fact that Sentinel images hosted on the Google Earth Engine (GEE) suffered from problems such as misregistration (Yan et al., 2018) and underestimating the presence of clouds through the QA60 band (Nguyen et al., 2020; Qiu et al., 2019), which may have changed the distribution of digital numbers at a pixel location and therefore affected the classification results. In the post-processing phase, the patches misclassified as other land covers were not paid sufficient attention to. For large-area mangrove mapping, correcting Sentinel images scene-by-scene is unpractical and requires enhanced post-processing solutions. For example, Hu et al. (2020) acquired a total of 6,179 Sentinel-1 images and 22,371 Sentinel-2 images to derive the new mangrove map of China.

To reduce the number of missing mangrove patches through enhanced post-processing, the use of multi-temporal high-resolution images with high accessibility should be introduced. In previous Sentinel-based mangrove mapping efforts, Google Earth imagery, which provides both the latest and historical imagery with a spatial resolution of less than 1 m, has only been used as an auxiliary source of data in sample collection and evaluation. Therefore, Google Earth imagery could be used in the enhanced post-processing that would assist the procedure of fixing the missing patches by manual editing and increase the accuracy of the final product.

To produce an accurate, up-to-date and detailed mangrove map of China based on 2019 Sentinel data, we applied an approach that combines the classification method by Zhao and Qin (2020) with enhanced post-processing for correcting missing mangrove patches that uses Google Earth images. The remainder of the paper is structured as follows. Section 2 describes the applied approach and evaluation methods. Section 3 shows the evaluation results of the new mangrove map and compares it with other products. Section 4 provides the link to the access to the data, and Section 5 presents the conclusions and future work to further improve the mangrove map.

## METHODS

### Data sources

Since mangroves are sensitive to low temperatures (Chen et al., 2017b; Stuart et al., 2007), their potential area does not change much within a period of 2 years. Thus, we reused the

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**FIGURE 1** The potential area of mangroves in China
potential mangroves area (Figure 1) defined by Zhao and Qin (2020) with a northern latitudinal limit of 31.18° that is about 3°higher than the northern limit of mangroves in the Yueqing Bay (28°20′N) of China. The extent (3.83°N to 31.18°N, 108.02°E to 122.95°E) was divided into 1’ × 1’ cells to be consistent with the resolution of Earth Topography 1 arc-minute (ETOPO1) data, which integrates land topography and ocean bathymetry (Amante & Eakins, 2009). The area was then filtered using ETOPO1 with an elevation threshold between −25 and 30 m, ALOS World 3D-30 m (AW3D30) DEM, which provides terrain information from 2006 to 2011 (Tadono et al., 2016), and a tidal flat map of southern China in 2017 integrating water salinity types (Zhao et al., 2020). AW3D30 was used to identify lower-altitude cells with an elevation below 25 m (about two times the maximum height of mangroves in China), which might be weighted to be high within a 1’ × 1’ cell (e.g. a long strip of beaches lying in front of a mountain). The tidal flat map was used to identify intertidal cells. Finally, the cells meeting the filtering thresholds were merged by union to define potential mangrove areas. The potential areas were intentionally defined to be much larger than the actual mangrove distribution, to avoid omitting any mangroves in China.

In the classification, we used the same data sources used by Zhao and Qin (2020), but updated the time period to extend from July 2018 to July 2020 in order to derive the mangrove map for 2019. The data sources included time series of Sentinel-1 Synthetic Aperture Radar (SAR) and Sentinel-2 optical images provided by the European Space Agency, as well as AW3D30 data provided by the Japan Aerospace Exploration Agency. All the data were hosted on the GEE platform with public access. The Sentinel-1 SAR images (https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S1_GRD) have two bands that are sensitive to the physical properties of mangroves. Optical images (https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2) have a larger number of bands that reflect the biochemical properties of mangroves. We chose the top-of-atmosphere reflectance data rather than the surface reflectance data because these were incomplete for China for the study time period. The images with a cloudy pixel percentage of less than 20% were selected and masked with the QA60 band to reduce the effect of clouds. The time series was reduced to quantiles to describe mangroves with more detail. AW3D30 data (https://developers.google.com/earth-engine/datasets/catalog/JAXA_ALOS_AW3D30_V1_1) provide terrain information to identify low-lying vegetation, including mangroves.

For the enhanced post-processing, we used the tidal flat map of southern China in 2017 (Zhao et al., 2020) to identify mangrove growing areas and used Google Earth images to identify the missing patches. We not only emphasized the mangroves in marginal climates (i.e. mangroves at their poleward limits) but also examined the mangroves growing in suitable climates because they also have small mangrove patches and parts of the large mangrove patches can also be misclassified as other land covers.

### 2.2 Classification

We used a detailed classification scheme modified from Zhao and Qin (2020). The modified scheme removed the class of salt marsh that was dominated by the widespread invasive *Spartina alterniflora*, which shares similar niches with the mangroves (Chen et al., 2009; Li & Lee, 1997; Yang et al., 2018), because we found that the edges of the mangrove patches were easily misclassified as salt marshes. These errors may result from the sparse mangroves at edges mixing with tidal flats, which reduces their greenness. According to the comparison results in Zhao et al. (2020), a majority of the salt marshes could be classified as tidal flats as in Murray et al. (2019), when the class of salt marsh was absent. After that, land covers of coastal areas were classified into nine classes (Table 1).

| Class             | Description                                                      |
|-------------------|-----------------------------------------------------------------|
| Mangroves         | Trees, shrubs and palms that strictly distribute in the intertidal environments (Tomlinson, 1986) |
| Coastal forests   | Salt-tolerant forests near mangroves, such as *Cocos nucifera* Linn., *Casuarina equisetifolia* Linn. and associate mangrove species |
| Terrestrial forests | Forests that are far from the intertidal zone                   |
| Grass             | Herbaceous vegetation outside of the intertidal zone             |
| Cropland          | Cultivated land that is dominated by rice                        |
| Tidal flats       | Bare land that is frequently inundated by water                  |
| Sand or rock      | Sandy and pebble beaches or rocky coasts                         |
| Permanent water   | Lasting water area that is not affected by seasonal change       |
| Impervious surfaces | Artificial structures such as residential areas, roads and construction areas |

**TABLE 1** Classification scheme adopted in this study
We used the same training samples and classification methods as Zhao and Qin (2020). The samples were composed of 16,444 points selected through the authors’ visual inspection on Google Earth; these data can be publicly accessed (https://doi.org/10.11922/sciencedb.00279). Since there was a short time lag between the two time periods, it is acceptable to use them for classifying coastal land covers in 2019. A total of 47 features were used in the classification, including features synthesized from multiple quantiles (5%, 15%, 25%, 35%, 50%, 65%, 75%, 85% and 95%) on SAR bands (i.e. VV and VH) in combination with ratios calculated from the optical bands (i.e., normalized difference water index – NDWI and normalized difference vegetation index – NDVI) to describe the inundation and greenness states of the land covers, features synthesized from the 50% quantile on other multi-temporal bands (R/G/B/NIR bands with 10-m resolution, Red Edge/SWIR bands resampled to 10-m resolution) to estimate the normal state of the land covers and DEM to identify low-lying vegetation. We classified coastal land cover using the random forest algorithm on the GEE platform based on its computation efficiency. The details on the classification method can be found in Zhao and Qin (2020).

2.3 Enhanced post-processing

We extracted the mangrove class within a 30-m buffer around the tidal flats (i.e. we selected the polygons that intersected the buffer). In addition to normal visual checks (i.e. elimination of obviously false mangroves and addition of true mangroves (Tomlinson, 1986) that were classified correctly but fell outside the buffer), we utilized Google Earth images to repair the missing patches in both marginal and suitable climates through manual editing.

For mangroves at the margins of their preferred climate, tidal flats were occupied by *S. alterniflora* (Chen et al., 2009; Mao et al., 2019). Recent studies showed that *S. alterniflora* senesces in winter (Tian et al., 2020), while mangroves are evergreen (Chen et al., 2017a). We used winter historical images to avoid that the mangroves would be covered by *S. alterniflora*.

Because of their water dispersal reproduction strategy (Clarke, 1993; Di Nitto et al., 2013; Wang et al., 2019b), mangroves may spread to other places. We not only checked the identified patches and land covers near the patches but also the land covers in similar environments within a range of several kilometres to avoid omitting misclassified mangroves, especially newly reproduced mangroves in suitable climates.

Because of afforestation efforts, there are also many young planted mangrove stands. The newly planted seedlings are not visible in Google Earth images; after growing for a period of one or two years, they gradually become visible as green dots on tidal flats. We adopted polygons to denote the areas with dense green dots, because the canopy density in the areas with sparse green dots is too low to determine a clear boundary.

2.4 Evaluation methods

To evaluate the newly produced mangrove map and compare, it with existing maps (i.e. the collected five mangrove maps including the LT_Map by Jia et al., 2018; the SV_Map by Hu et al., 2018; the P_Map by Chen et al., 2017a; the LA_Map by Bunting et al., 2018 and the PXL_Map by Zhao & Qin, 2020), we used the same evaluation data sets.

We conducted an accuracy assessment based on the same validation data sets from Zhao and Qin (2020) in view of the need for comparisons and the short time lag between the two time periods. The validation data sets contain 10 sampling results, each of which was constructed by a simple random sample with replacement and has a sample size of 1,200 (i.e. mangroves and non-mangroves each account for 50%) from a population of 4,486 samples (Figure 2). We repeated the validation 10 times because the number of non-mangrove samples in the validation set is about 6 times that of the mangroves and a direct validation would lead to an overall accuracy bias in the accuracy of non-mangroves. Therefore, the accuracy can be described by the mean overall accuracy and its standard deviation. All the maps were validated by the data sets for comparison.

In addition to the validation data sets, we evaluated the maps by field sample plots carried out in 2017 and 2018 (Figure 3). A total of 1,096 sample plots were collected in four provinces and one autonomous region (i.e. the provinces of Zhejiang, Fujian, Guangdong and Hainan, as well as Guangxi Zhuang Autonomous Region). The way of creating sample plots is presented as follows by taking Guangxi Autonomous Region as an example. In Guangxi, mangrove experts set up 30 survey sections, which were independent from remote sensing-based processes in this study. For each survey section, there is one survey site in each of the upper intertidal zone, middle intertidal zone and lower intertidal zone. In view of a certain survey site, three 10 m × 10 m sample pots were set up with the purpose of obtaining the mangrove properties. In summary, there were a total of 270 sample plots in Guangxi. The sample plots were recorded by centre coordinates. Therefore, these sample plots, which were determined by mangrove experts and independent to this study, are suitable for validating mangroves derived in this study. We measured the accuracy of these mangrove maps by the rate between the identified sample plots and the total number of sample plots, in which a sample plot was identified if there was a polygon.
intersecting a 5-m buffer of the centre coordinate. All the mangrove maps were evaluated because most of them had not been verified by field samples.

Mangroves in marginal climates have been historically neglected by mangrove maps due to their small size and different appearance from most mangroves. We used field...
survey data from mangrove specialists to evaluate the performance of these maps in identifying mangroves in marginal climates. The survey investigated planted mangroves in Zhejiang Province (Wang et al., 2020). The survey identified seven mangrove planting areas with a criterion of a presence of mangroves on the tidal flats (Figure 4a), which was independent of the remote sensing-based mangrove identification. We counted the number of identified mangrove planting areas and summarized the area of correctly identified mangroves (Kamal et al., 2015) to measure the ability to identify mangroves in marginal climates, in which a mangrove planting area was identified if there were polygons near a planting area.

We also evaluated the performance of these maps for identifying mangroves in suitable climates. We selected two cases for comparison: one case is a typical distribution of fragmented small mangrove patches (Figure 4Ⅰ), and the other is a typical distribution of continuous large mangrove patches (Figure 4Ⅱ). For the fragmented distribution, we identified each small patch by visual inspection and marked it with a point at the centre. We measured the ability to identify small mangrove patches in suitable climates by counting the number of points that fall into the polygons and summarizing the area of correctly identified mangroves. For the continuous distribution, we compared these mangrove maps qualitatively.

### RESULTS AND EVALUATIONS

#### 3.1 Evaluation results of the mangrove maps by validation data sets

The mangrove map of China for 2019 derived from this study has an overall accuracy of $96.4 \pm 0.3\%$, and a median overall accuracy of $96.5\%$ based on the randomly generated 10 class-balanced validation sets (Table 2).

We also evaluated the other five mangrove maps with the same validation data sets (Figure 5). Considering the vast study area involved in mapping global mangroves, the low accuracy of the LA_Map (a subset of China of the global products) is reasonable. The Landsat-based maps increased the accuracy by more than 10% with the study area shrinking to China. And the Sentinel-based maps further increased the accuracy by more than 8% on the basis of Landsat-based maps. Compared with the PXL_Map, this map increased the accuracy by about 1%. As mangroves cover a very small percentage of the potential area, the improvement makes sense.

Although the time difference may affect accuracy, the variation on accuracies of the mangrove maps for 2015 (i.e. LT_Map, SV_Map and P_Map) showed that other factors (e.g. data sources, classification algorithms and post-processing methods) had a greater impact on the accuracy.
3.2 | Evaluation results by field sample plots

The accuracy of the produced mangrove map of China for 2019 reached 96.2% using a total of 1,096 field sample plots and achieved the highest accuracy at the provincial level (Table 3).

In general, the accuracies measured by field sample plots are consistent with those measured by validation data sets. The Sentinel-based maps had higher accuracies than the LA_Map and the Landsat-based maps. Compared with the PXL_Map, the produced mangrove map increased the accuracy by about 4%. At the provincial scale, the produced map largely improved the accuracy in Zhejiang Province due to the enhanced post-processing, which is discussed in detail in Sections 3.3.

### TABLE 2 | Confusion matrix of the produced mangrove map of China for 2019. It corresponds to the median overall accuracy from 10 validations

| Reference for PXL_Map | Non-mangroves | Mangroves | User’s accuracy |
|-----------------------|---------------|-----------|----------------|
| Non-mangroves         | 598           | 40        | 93.7%          |
| Mangroves             | 2             | 560       | 99.6%          |
| Producer’s accuracy   | 99.7%         | 93.3%     |                |
| Overall accuracy      |               |           | 96.5%          |

3.3 | Evaluation results by field surveys in marginal areas

The produced mangrove map identified six areas among a total of seven mangrove planting areas identified by Chen et al. (2020) and performed much better than the other five mangrove maps (Figure 6). This is also supported by the performance on the area of correctly identified mangroves.

The mangroves in marginal climates were hard to capture, especially when tidal flats were covered with thriving *S. alterniflora*. In the case of the LA_Map and LT_Map, phenology was not properly considered because Bunting et al. (2018) focused on the number of image scenes with certain cloud cover, and Jia et al. (2018) focused on the tidal status of single-date images. The remaining maps considered the phenology using multi-temporal images. The difference in the performance of the SV_Map and the P_Map may result from the post-processing, in which Hu et al. (2018) utilized a morphological filter to remove small patches and Chen et al. (2017a) applied a visual adjustment based on Google Earth images in addition to empirical constraints. Similarly, the better performance of the produced map benefits from the enhanced post-processing compared with the PXL_Map.

Since the survey did not provide a detailed distribution of mangroves, we used a subset of field sample plots to compare the field-based results and the RS-based results (Figure 7). The distance between the field sample plots in yellow and the nearest mangrove polygon is between 15 and 30 m, which is far from the threshold (i.e. 5 m) within which a field sample

### TABLE 3 | Accuracy of mangrove maps measured by sample plots data. The number of sample plots in each province is shown in parenthesis

| Province | LA_Map | LT_Map | SV_Map | P_Map | PXL_Map | This map |
|----------|--------|--------|--------|-------|---------|---------|
| Guangxi (270) | 65.2%  | 77.0%  | 90.7%  | 91.1%  | 94.8%   | 98.1%   |
| Guangdong (376) | 55.3%  | 74.2%  | 80.9%  | 83.5%  | 89.6%   | 93.4%   |
| Hainan (237) | 88.2%  | 89.5%  | 89.0%  | 94.1%  | 93.7%   | 97.9%   |
| Fujian (189) | 49.2%  | 87.8%  | 84.7%  | 92.1%  | 98.4%   | 99.5%   |
| Zhejiang (24) | 0.0%   | 12.5%  | 4.2%   | 25.0%  | 33.3%   | 75.0%   |
| Total (1,096) | 62.4%  | 79.2%  | 84.0%  | 87.8%  | 92.1%   | 96.2%   |
plot was identified. Although no mangroves could be visually identified on the image (a historical image dated 27 January 2019, from Google Earth), the newly planted seedlings were visible in the field survey. After a period of growth, the seedlings would appear on the image as green dots (Figure 7I). The dense portion of the dots may be neglected by the classification, thus manual editing was done. Due to the 10-m resolution of Sentinel images, the border of mangrove polygons identified by the classification algorithm does not fully match the mangroves on Google Earth image with a resolution higher than 1 m (Figure 7II). There is a time lag between mangroves being planted and mangroves becoming visible on the images; this is also an important reason for updating mangrove maps, in addition to monitoring mangrove deforestation.

In addition to the mangrove planting area in Figure 8, the produced mangrove map may have also missed other newly planted mangroves in the seven mangrove planting...
areas because seedlings were invisible. Afforestation efforts have accelerated the expansion of mangroves, but their survival is still determined by a changing climate (e.g. frequency of cold events and precipitation) (Chen et al., 2017b). Therefore, it is important to pay attention to these mangroves as climate indicators in addition to their ecological and societal values.

### 3.4 Evaluation results by cases in suitable areas

The produced mangrove map identified 29 patches out of a total of 45 fragmented small mangrove patches. The number of identified fragmented small mangrove patches varied across different mangrove maps (Figure 9), while the produced mangrove map was second only to the PXL_Map.

Among the mangrove patches in suitable climates (Figure 10), all the mangrove maps identified the patches located in the northern part of the subplot, and the Sentinel-based maps (Figure 10e,f) delineated their boundaries with more detail than the other four maps. Among the four maps, the P_Map performed better than the other three, which was consistent with the accuracies measured by the validation data sets, field sample plots, and a number of identified mangrove planting areas. Even so, the patches identified by the P_Map are only about half of those identified by Sentinel-based maps.
Because mangroves are widespread in suitable climates and because we used 10-m-resolution data for the classification, we paid more attention to removing other land covers misclassified as mangroves. Using high spatial resolution images (finer than 1 m), these small mangrove patches may be easily identified.

The maps show similar results for the continuous large mangrove patches (Figure 11), except that in the LA_Map and the PXL_Map they were more fragmented. The performance of the LT_Map may benefit from an object-based image analysis, which segments adjacent homogeneous pixels into objects (Blaschke, 2010; Dronova, 2015). A visual analysis indicates that the produced map has relatively neat and clean boundaries.

3.5 Distribution of mangroves

Figure 12 shows the mangrove map of China for 2019 produced in this study. According to the above detailed evaluation, this map has a significantly higher accuracy than other mangrove maps. The mangrove area decreases with increasing latitude, which is reflected by the rapid shrinking of subplot sizes.

Based on the produced map, the total mangrove area of China in 2019 was calculated to amount to 25,585 ha using an Albers conic equal-area projection (Table 4). Mangroves in Guangdong have the largest extent (about 42.0% of the mangrove area in China), followed by Guangxi (about 30.6%) and Hainan (about 17.7%). Approximately 90.3% of mangroves are concentrated in these three provinces.
The produced map focused on the exact locations and boundaries of individual mangrove patches rather than on the total area of mangroves. There are both commission and omission errors in the produced map. For example, some non-mangroves are misclassified as mangroves (e.g. *S. alterniflora*, forests neighbouring mangroves and tidal freshwater forests (Chen et al., 2017a; Gao, 1998; Spalding, 2010), and some mangroves are misclassified as non-mangroves (e.g. mangrove patches are missing even after enhanced post-processing).

Although fragmented mangrove patches add little to the total area of mangroves in China, they contribute to local coastal resilience by supporting species movements and dispersal (Curnick et al., 2019; Triest, 2008). The small mangrove patches, especially the ones in marginal climates, increase community diversity and habitats for different species (Barbier et al., 2008; Dobson et al., 2006; Lindenmayer, 2019; Montoya et al., 2012). Thus, a focus on mangrove patches, regardless of their size, is important.

### DATA SET ACCESS

The mangrove map of China for 2019 is available at the Science Data Bank (https://doi.org/10.11922/sciedb.00245). This map is the first publicly accessible detailed mangrove map.
derived from combining 10-m-resolution classification results from Sentinel images with enhanced post-processing based on submetre resolution Google Earth images, which has been manually edited to repair broken boundaries that are common in remote sensing-based mangrove maps. The map has a particular focus on fragmented small mangrove patches in marginal climates. This focus helps to monitor the poleward expansion of mangroves resulting from afforestation efforts.

The related data were also open-accessed, including a mangrove map of China for 2017 available at the Science Data Bank (https://doi.org/10.11922/sciencedb.00479), a tidal flat map covering mangroves of China for 2017 available at the Science Data Bank (https://doi.org/10.11922/sciencedb.00481), and a validation data set for mangroves available at the Science Data Bank (https://doi.org/10.11922/sciencedb.00279).

5 | CONCLUSIONS

In this study, we produced a detailed mangrove map of China for the year 2019. The map was derived from the classification of satellite images and an enhanced post-processing. For the classification, we synthesized quantiles as features from the time series of Sentinel-1 SAR images, Sentinel-2 optical images, as well as AW3D terrain data, and classified them on the GEE platform. In post-processing, we applied manual editing based on Google Earth images to correct missing mangrove patches. The final map achieved an overall accuracy of 96.4 ± 0.3% based on validation data sets, and an accuracy of 96.2% based on a total of 1,096 field sample plots. Based on the same evaluation data, the map not only outperformed other existing maps in general evaluations, but also better identified small mangrove patches, in both marginal and suitable climates, and identified large mangrove patches with neater and cleaner boundaries. According to the produced mangrove map, the total mangrove area of China in 2019 was 25,585 ha.

To the best of our knowledge, this map is the first publicly accessible detailed mangrove map derived from combining 10-m-resolution classification results from Sentinel images with enhanced post-processing based on submetre resolution Google Earth images. This map has a particular focus on fragmented small mangrove patches in marginal climates. This focus helps to monitor the poleward expansion of mangroves resulting from afforestation efforts. In addition, the map has been manually edited to repair broken boundaries that are common in remote sensing-based mangrove maps.

In addition to serve as a basis for applications such as mangrove species mapping, leaf area index estimation and carbon stock assessment, the map can also improve other mangrove maps by mutual correction. Future work will focus on developing mangrove maps with a spatial resolution of less than 1 m by an automatic or semi-automatic mangrove mapping approach.

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OPEN PRACTICES

This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available at https://doi.org/10.11922/sciencedb.00245. Learn more about the Open Practices badges from the Center for OpenScience: https://osf.io/tvyxz/wiki.

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