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An improved quality assessment framework to better inform large-scale forest restoration management

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ABSTRACT

Dynamic monitoring of forest ecosystem quality is necessary for restoration program evaluation but remains challenging for very large-scale programs. Current evaluation methods employ regional forest quality indicators that compare the quality status of targeted forests with benchmarks from remnant old-growth forest communities, however data availability usually limits the application of available methods to small scales. We constructed an improved framework, integrating forest site classification selection and local remnant old-growth forest community delimitation, to quantify and map forest quality using environmental data and remote sensing (RS) based approaches. A classification strength model was introduced to improve the accuracy of forest site classification. The remote-sensing-based method integrates species composition and forest biological productivity characteristics recognition to develop a practical tool for large-scale remnant old-growth forest community delimitation. The new assessment framework was tested across the entire spatially heterogeneous Yangtze River Basin, the largest watershed in China and showed high accuracy in forest quality assessment based on observed field data validation. The forest site classification was selected by considering spatial heterogeneities in climate, topography and soil type, with 37 forest sites classified. The native forest community groups with less human disturbance in each forest site used for forest quality baseline estimation were also selected as forests with top 10% of biomass in protected areas. The case study demonstrated that forest areas of low and poor quality accounted for 34.46% of the total forest area in 2015. Between 2000 and 2015, 55.72% of forest areas experienced increases in quality level, and 7.07% experienced decreases. The improved forest quality assessment framework enhances the scope and accuracy of forest restoration information and can be applied as an evaluation tool for forest restoration management.

1. Introduction

The world has become a "greener" place than it was 20 years ago, with respect to an expansion in leaf coverage, as a consequence of increased forest restoration in response to policy drivers (Chazdon et al., 2017). China is a leading country in expanding forest cover through restoration, with major policy initiatives including the Grain to Green and Natural Forest Protection programs, accounting for 25% of the global net increase in leaf area (Chen et al., 2019). However, increasing forest coverage across the globe does not necessarily mean the functionality of the forest (i.e., biomass, carbon sequestration) is being restored at the same rate or to the same levels (Mansourian, 2018). Newly planted forests, established without full consideration of the restoration of ecological functions, can be vulnerable to human and natural disturbances in comparison to natural extant forests because of uneven distribution of planted species, poor structural restoration, and overuse of ornamental, easily propagated and fast-growing species (Ren et al., 2017). As a consequence, forest degradation has been observed in afforestation project regions in China, and shown to cause serious perverse environmental outcomes including desertification and soil erosion (Lai et al., 2013; Zhang et al., 2017; Peng & Li, 2018). These perverse outcomes underscore the urgent need for dynamic forest ecosystem

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monitoring to more effectively evaluate forest ecosystem quality and quantitatively analyze the progression of large-scale forest restoration management (i.e., nation, continent, globe).

Forest ecosystem quality, that is the naturalness (with respect to a reference) of the forest structure, biodiversity composition and function, can provide information about the state of the forest and progress in forest restoration efforts (Liira et al., 2007). Forest quality depends on important state factors, including factors related to the initial state of the ecosystem (i.e. climate, topography, parent material, potential biota), external condition factors (i.e. human activities) and ecosystem age factors (i.e. time) (Amundson & Jenny, 1997). Site conditions in particular (e.g., climate, topography, soil), play a key role in determining forest quality levels and restoration potential. Ideally, in a given zone with homogeneous site conditions, forests with spontaneous, unmanaged regrowth can potentially be restored to the quality status of the remnant old-growth forest community (Ruiz-Jaen & Mitchell Aide, 2005). Based on a comparison with the remnant old-growth forest community, forest quality indicators can be constructed to inform forest restoration management (Czúcz et al., 2012; Scholes & Biggs, 2005).

Usually, forest quality indicators used for small spatial scale applications are aggregated indexes (such as tree attributes, plant species diversity and forest biological productivity) encompassing more detailed information about the structure, biodiversity composition and function of the forest ecosystem (Fernandes et al., 2010; Ferrari et al., 2009). But for large-scale forest restoration management, data availability is the basis for constructing forest quality indicators, as aggregated indexes based on field surveys or long-term monitoring have failed at large-scale applications because of their time-consuming data collection process. For forest restoration with natural regeneration, forest biomass carbon storage affected by forest structure (i.e., leaf area) and species diversity (i.e., functional divergence) (Vellend et al., 2010; Poorter et al., 2016; Becker et al., 2011) is an important ecosystem service (Ouyang et al., 2016) and the main driver of changes in ecosystem process recovery rates after disturbance (Lohbeck et al., 2015). In spontaneous, unmanaged forests regrowth process, the relative biomass of degraded forests to the remnant old-growth forest community can reflect the recovery status of forest restoration, and biomass accumulation or decrease can indicate the success of restoration or degradation of forest quality (Liu et al., 2017). Remarkably, in forests that are managed for timber production instead of forest restoration (e.g., boreal forests and tropical plantation forests), there is no close link between forest biomass and the suite of ecosystem services, diversity and structure. Additionally, researchers have provided many available methods to estimate forest biomass stock at the global and national scale, and herein the relative biomass stocking of forests can be relative easily achieved and used as the forest quality indicator to inform large-scale forest restoration (Roxburgh et al., 2019; Sun et al., 2014; Fedrigo et al., 2014).

Among the large-scale forest quality assessment researches, several researchers have built the complicate ecological models to estimate remnant old-growth forest community biomass carrying capacity at pixel scale as the benchmark (Keith et al., 2010; Roxburgh et al., 2006; Fedrigo et al., 2014). Although these methods can provided more acuurate forest quality estimation, the large database is still needed and raise difficulty in large scale application (Roxburgh et al., 2019). Some researchers have provided the simper method to estimate the quality baseline at regional scale based on forest site classification. These methods evaluated forest quality by setting remnant old-growth forests in the same forest site, the homogeneous region with same biotic land features where forests can be restored at same level, as the baseline and calculating the relative value with local forest quality baseline obtained by field survey as the quality indicator (Czúcz et al., 2012; Xiao et al., 2016). Although this method provides an easily adaptable approach to assess the large-scale forest quality, there are two main challenges for more accurate and practical application.

For large scale forest quality assessment, one of the major premises for comparison with remnant old-growth forest communities is the identification of homogeneous forest sites, which directly impact the accuracy of forest quality estimation. When classifying homogeneous forest site condition zones, different levels of homogeneity can be distinguished at different spatial scales (Klijn 1994). The leading environmental factor determining site classification at a given location varies at different spatial scales. For example, at the global or continental scale, climate is usually used as the dominant factor in forest distribution (Mackey et al., 2007), while topography and soil type determine forest classification at finer scales (Leathwick et al., 2003; Mcmahon et al., 2004). As a consequence, many forest site classifications based on selected scale, dominant environmental factor or method of classification (both quantitative and qualitative approaches) have been used to classify forest land into different homogeneous areas (Czúcz et al., 2012; Xiao et al., 2016). However, this diversity of forest site classification schemes means that agreement on accurate and consistent classification remains difficult (Barton & Metzeling, 2004; Andrew et al., 2013).

Another challenge for classifications based on comparisons with remnant old-growth forest communities is the identification of remnant old-growth forest communities for baseline establishment. Field survey data and remote sensing (RS) images are often used for forest quality baseline estimation. Some studies have obtained remnant old-growth forest quality baseline using sample-based methods like field surveys or forest inventory (Czúcz et al., 2012; Xiao et al., 2016). Although these methods can provide accurate information about remnant old-growth forest communities and have been widely applied at large scales, they may involve time consuming data collection (Feng et al., 2016) in remote locations. Some research has demonstrated more easily adapted approaches based on RS image analysis (e.g., NDVI, biomass) to delimit the remnant old-growth forest communities based on recognition of distinguishing characteristics (i.e., species composition, vegetation structure, stability, naturalness) (Cunningham et al., 2017; Fernandes et al., 2010; Ferrari et al., 2009; Winter, 2012). However, these methods are based on the use of coarse resolution RS data and consequently have large uncertainty around evaluation accuracy due to a lack of indicators for comprehensively describing remnant old-growth forest characteristics (Huang et al., 2020; Dong et al., 2018). There is still a limited set of methods available to quickly and accurately estimate forest quality baselines at large scales.

To overcome the above challenges, a framework for assessing forest ecosystem quality at large scale was established by integrating forest site classification associated with a classification strength model, and forest quality baseline estimation based on native forest community and biomass characteristics recognition. The framework is applied to a case study in the Yangtze River Basin, the largest river basin in China, where forest ecosystems make up 34.2% of the total land area and many forest restoration projects have been implemented. The specific goals of this study are to (1) establish an improved forest site classification method for forest quality assessment; and (2) establish a more practical and accurate method for quality baseline estimation based on forest site classification to better inform forest restoration practice. The framework can be applied in any region with remote sensing forestry data to provide robust evidence of forest conservation and restoration management (Zheng et al., 2019).

2. Framework for forest ecosystem quality assessment

The framework for forest ecosystem quality assessment includes 5 steps (Fig. 1) based on forest site classification associated with classification strength analysis and forest quality baseline estimation based on remnant old-growth forests delimitation.

2.1. Step 1: Forest ecosystem recognition and biomass retrieval

To assess large-scale forest quality, the data sources, the extent of

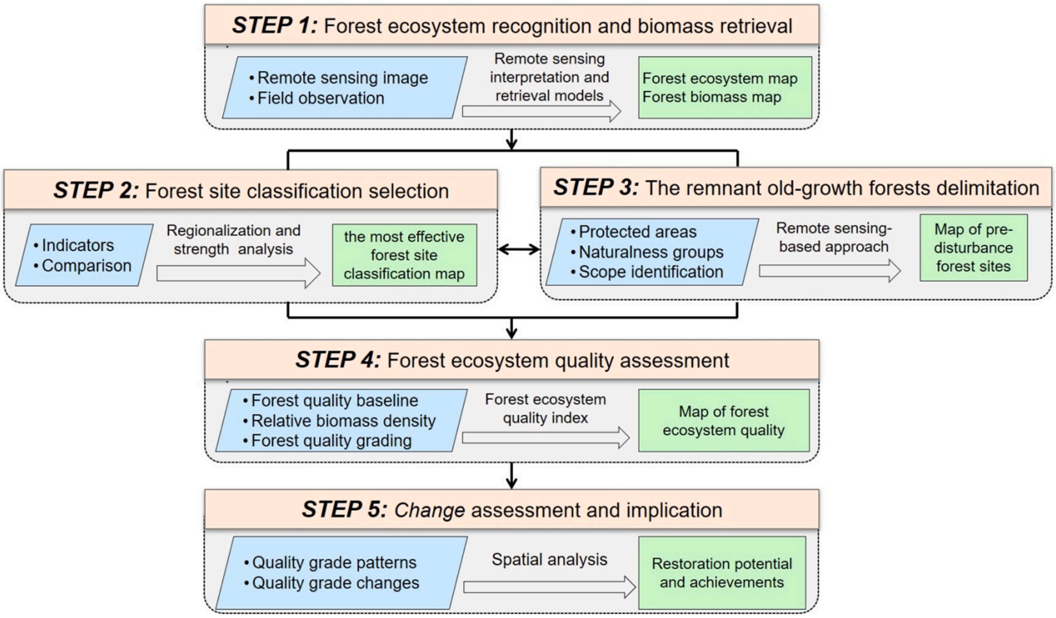

Fig. 1. Framework for forest ecosystem quality assessment.

forest ecosystem and the quality indicator, should be determined. Remote sensing-based methods combined with field data validation is usually used for large-scale forest ecosystem recognition (Dong et al., 2018; Ouyang et al., 2016). The forest ecosystem map can be derived from a small satellite constellation (HJ-1A/B) and Landsat OLI (resolution 30 m) images using object-oriented multi-scale segmentation and decision tree procedures (Kong et al., 2018). For the forest quality indicator, the forest aboveground biomass which can reflect changes in forest biological productivity and has been widely used for forest restoration management (Roxburgh et al., 2019), can be used. Then, forest aboveground biomass can be retrieved by using the LAI (leaf area index) product derived from Terra MODIS (resolution 250 m) and validated by measured aboveground biomass data from field surveys (Huang et al., 2020).

2.2. Step 2: Forest site classification

The forest site classification is defined as any form of classification system that stratifies biotic and/or abiotic land features using methods that aggregate, divide, sort, synthesize, and/or integrate into classes the different components of the forest environment (such as climate, topography, soil, and vegetation) (Louw & Scholes, 2002). Forests of the same forest site type, i.e. areas with relatively homogenous soils, climate, parent material and topography (Ruiz-Jaen & Mitchell Aide, 2005), can be restored to the same level. Forest quality assessment based on forest site classification provides a practical approach for large-scale application. Various forest site classifications have been developed based on different site condition factors and classification methods. Because there is no optimal, singular forest site classification available at the different scales of to which planning extends (Mackey et al., 2007), it is essential to select the proper forest site classification, effectively characterizing the variance in quality baselines for each forest site in the planning area, among different classification schemes. The proper classification can be selected based on the classification strength model which can test the classification effectiveness by quantifying within- and between-class variability (Ludwig & Reynolds, 2019). The forest site classification with the highest classification strength indicates that the classification can effectively capture the quality baseline pattern in the planning area in comparison to other classifications and can be selected for the next step in analysis.

2.3. Step 3: The remnant old-growth forests delimitation

Since remnant old-growth forests are usually used as the benchmark for forest restoration (Czúcz et al., 2012.), the delimitation of these forests is essential for forest quality assessment. Remnant old-growth forests can be viewed as the native forests with relatively little human disturbance and are highly distributed in the widely established protected areas (Bristow, 2009) designed to capture high remnant naturalness. The species of natural forests can be delimited by vegetation naturalness analysis (McNaughton, 1977; Tilman & Downing, 1994) and human influence can be monitored using the status of forest biological productivity. The native forests with stable productivities indicating no sign of human logging in the protected areas can be delineated as remnant old-growth forests and used for quality baseline analysis (Terhorst & Munguia, 2008; Chen et al., 2015).

2.4. Step 4: Forest ecosystem quality assessment

Relative stocking of biomass is the key indicator for forest restoration assessment and reflects the time since forest restoration/tree planting. The longer the time since tree planting, the greater the biomass and the higher the relative stocking of biomass. The mean biomass of remnant old-growth forests in each forest site based on forest site classification is calculated as the forest biomass baseline for forest quality assessment. Forest quality is assessed at the raster scale using the relative biomass density model which compares the relative resemblance of a specific forest's biomass with its local forest biomass baseline.

2.5. Step 5: Change assessment and implication

The spatial patterns and changes in current forest ecosystem quality are analyzed. The assessment results can be used for evaluating progress in forest restoration management and can provide detailed information about potentially degrading areas requiring management intervention.

3. Case study

3.1. Study area

The Yangtze River Basin encompasses nearly 1,800,000 km^2 of land, with forests accounting for 34.2% of the land cover. The terrain of the basin changes substantially from the upstream area where the average elevation is over 3000 m above sea level, to the downstream area where the average elevation is about 100 m (Gong et al., 2006). The complexity of the terrain also results in a heterogeneous climate and diverse soil conditions (e.g., purple, lime and red soils) across the basin. The variety of climate, terrain and soil conditions determines the variety of forest communities in the basin, including the vertical belts of forest vegetation from the subtropical evergreen broadleaf forests in the midstream and downstream mountainous areas to the subalpine dark coniferous forests located in the upstream alpine valleys. The diversity of forest types provides excellent conditions for testing the forest quality assessment framework.

Because the Yangtze River Basin is also the most densely populated and agriculturally productive area in China, the original vegetation has been seriously degraded and replaced by naturally regenerated secondary forests from the 1960 s onwards (Kong et al., 2018; Chen et al., 2005). Many forest protection and restoration policies have been implemented in the Yangtze River Basin since the 1970 s. Forest protected areas are firstly established to conserve vulnerable forest resources and halt biodiversity declines caused by human overuse. To date, forest protected areas have been established across the basin, and include all forest ecosystem types within a total network of 382 designated sites (Fig. 2). From the 1990 s onwards, many forest restoration programs have been implemented, such as the Conversion of Cropland to Forest program and the Natural Forest Protection Project. These programs have led to huge improvements in vegetation coverage and the ability of the basin to supply ecosystem services (Ouyang et al., 2016). However, the current quality of forest ecosystems has not yet been evaluated. It is essential to evaluate forest ecosystem quality and analyze trends in quality to inform future forest conservation and restoration management.

3.2. Methods

3.2.1. Data sources

The data used in our study were obtained from the sources given below.

(a) The forest ecosystem maps (2000 and 2015) (resolution 90 m) were obtained from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences.

(b) Data on simulated forest aboveground biomass (2000 and 2015) (resolution 250 m), estimated by empirical models from remote sensing, was also obtained from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences. Data on measured forest aboveground biomass of remnant old-growth forests was obtained by field surveys in the Yangtze River Basin between 2011 and 2013. The 114 forest sites sampled were selected from areas with low patch fragmentation and uniform vegetation distribution. Three sample plots (60 m × 60 m) separated by 100 m were sampled at each site to ensure representativeness.

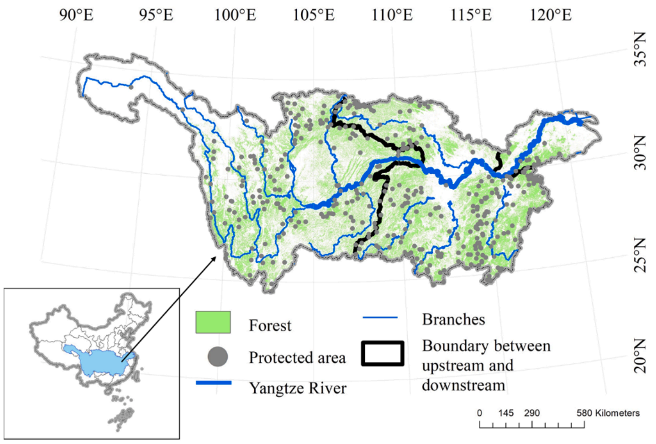

Fig. 2. Location, ecosystems and forest protected areas of the Yangtze River Basin.

(c) The Digital Elevation Model (DEM) used was obtained from the U. S. Geological Survey (USGS) (resolution 90 m).

(d) Soil classification and data on associated soil attributes (including topsoil organic carbon and topsoil pH) were obtained from the 1:1 million digital Soil Map of China and the Second National Soil Survey of China.

(e) Average annual rainfall and temperature data (annual calculated temperature above 10℃, annual calculated temperature above 0℃) were obtained from the Institute of Geographical Sciences and Natural Resource Research in China.

(f) The map of the distribution of forest protected areas in the Yangtze River Basin was obtained from the State Forestry Administration of China.

3.2.2. Forest ecosystem and biomass

We identified evergreen broadleaf forest, deciduous broadleaf forest, evergreen needleleaf forest, deciduous needleleaf forest, broadleaf and needleleaf mixed forest and sparse forest as the forest ecosystems and obtained a forest ecosystem map (2000 and 2015, at a resolution of 90 m) from Landsat TM/ETM + and OLI images using object-oriented multi-scale segmentation and decision tree procedures. We obtained the forest aboveground biomass map (2000 and 2015, at a resolution of 90 m) through LAI regression derived from Terra MODIS and validated with field-observed biomass ($R^2 = 0.85$, $P < 0.01$).

3.2.3. Forest site classification schemes

Climate, topography and soil conditions vary greatly across the Yangtze River Basin and jointly affect forest distribution (Amundson & Jenny, 1997). However, it is difficult to identify the principle factors determining forest community distribution. To select suitable classification indicators, we chose three methods of forest site classification for comparison. Although they are all based on site condition, each classification applies unique principles and emphasis.

(a) The Traditional forest site classification method considering accumulated temperature, precipitation and geomorphology. The first forest site classification is derived from the traditional forest site classification method used by the Chinese Academy of Forestry, where meteorological observation data (from 1980 to 2015) on precipitation and accumulated temperature above 10℃ are used to classify different climatic condition, and different geomorphology units based on DEM are used to reflect topographic differences (Zhang et al., 1992). Using this method, the Yangtze River Basin was divided into 24 forest sub-areas (Fig. 3a, Table S1).

(b) Revised forest site classification with topography. The method described in *(a)* above does not take forest vertical distribution into consideration which is an important factor in forest community distribution in the western alpine and gorges regions of the Yangtze River Basin. Thus, the second forest site classification (Fig. 3b) is derived by considering forest structure in relation to topography for the forest site sub-areas obtained from method *(a)* above, where forest stratification is based on altitudinal zonation. The standard for altitudinal zonation is based on previous research (detailed information in Table S2). Finally, the Yangtze River Basin was divided into 35 forest site sub-areas (detailed information in Table S1).

(c) Revised forest site classification with topography and soil. While method *(b)* allows classification based on improved climatic and topographic homogeneity data, it still does not take soil conditions into account. The third forest site classification (Fig. 3c, Table S1) is produced with the addition of soil classification to each class of the second forest site classification. The soil classification, Chinese soil taxonomy (CST), is based on the mechanical properties of soil, including permeability,

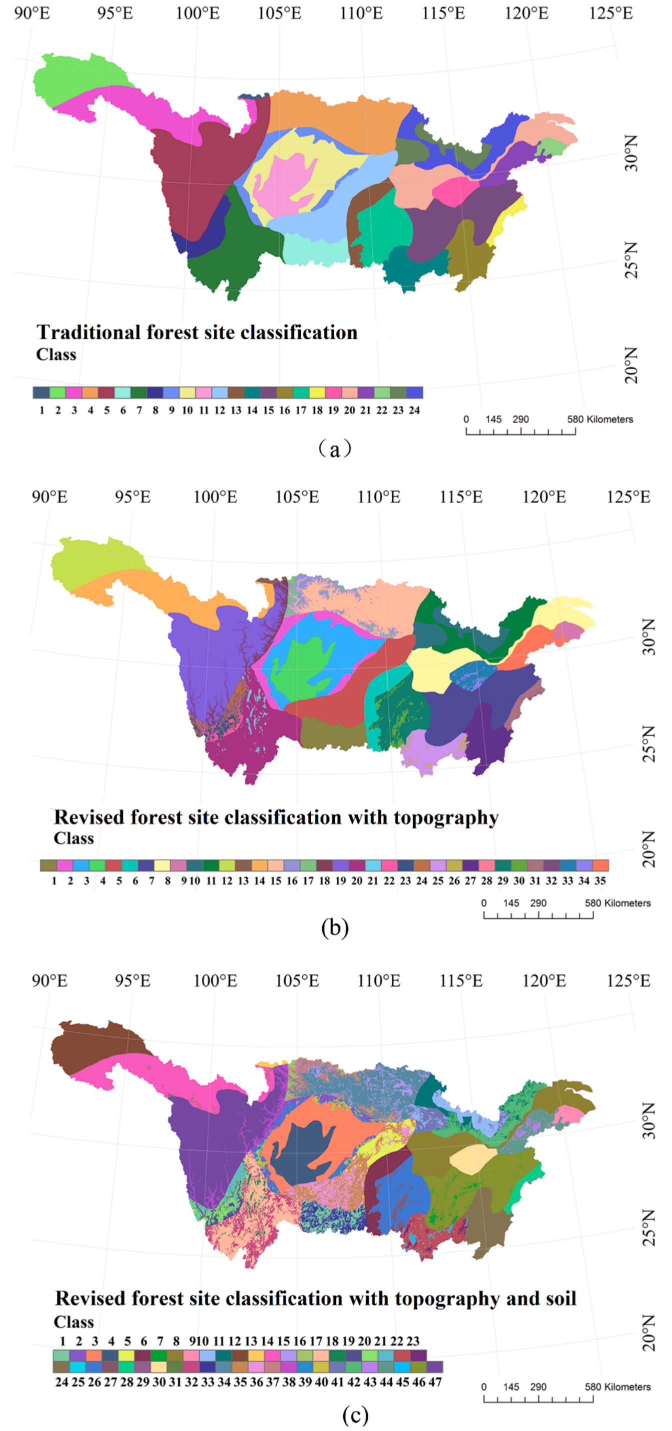

Fig. 3. Forest site classifications in the Yangtze River Basin based on different indicator systems: (a) traditional forest site classification based on accumulated temperature, precipitation and geomorphology, (b) revised forest site classification incorporating topography, and (c) revised forest site classification incorporating topography and soil attributes. (The detailed legend information is shown in Table S1).

stiffness, strength. Finally, the Yangtze River Basin was divided into 47 forest site sub-areas using the third classification scheme.

3.2.4. *Remnant old-growth forest delimitation*

Forest protected areas in the Yangtze River Basin are widely established and distributed in every forest class of the three forest site classification schemes. We used plant species composition and biomass to reflect human disturbance and selected native forest species groups with high and stable biomass in protected areas as the remnant old-growth forest community.

Firstly, we identified the native forest communities of each protected area (Table S3) based on the previous case study. The recognition of native forest communities was approached with the vegetation map (http://geodata.pku.edu.cn) (Ferrari et al., 2009). *Then* we used the status and stability of the biomass to select the native forest species with minimal anthropogenic disturbance since a high and stable biological productivity indicating no sign of human logging is one of the characteristics of remnant old-growth forests.

Six relatively high biomass forest quadrat groups (areas with the top 5, 10, 15, 20, 25, 30 percent biomass) in native forest communities of each protected area were chosen and then the groups with high stability based on a forest ecosystem stability index (FESI) were selected as the remnant old-growth forest community. The FESI was constructed based on the coefficient of variation of forest aboveground biomass (Chen et al., 2015). Considering stability is a fundamental characteristic of forest ecosystems, we used a divided linear strength method to define the extent of FESI from 10 to 100. FESI is calculated through contrast stretching the coefficient of variation of forest aboveground biomass data. In this study, the coefficient of variation of forest aboveground biomass data across 15 years (2000 to 2015) was used in the contrast stretching analysis. With x_{mean} as the arithmetic mean, σ as the variance, we use $x_{mean} \pm 2\sigma$ as the lower and upper limit in our analysis.

$$FESI_i = \left\{ \begin{array}{c} 10cv_i \geq cv_{max} \\ 10 + (cv_{max} - cv_i) \times acv_{min} < cv_i < cv_{max} \\ 100cv_i \leq cv_{min} \end{array} \right\}, \mathrm{a} = \frac{100 - 10}{cv_{max} - cv_{min}} \tag{1}$$

where cv_i is the coefficient of variation of forest aboveground biomass in pixel i, $FESI_i$is the forest ecosystem stability index in pixel i and is dimensionless and larger values indicate higher forest ecosystem stability, a is the strength constant, and cv_{max} and cv_{min} are the upper and lower limits of the coefficient of variation of forest aboveground biomass.

3.2.5. *Forest site classification strength calculation and selection*

We chose to use similarity analysis to validate the classification strength of different classification methods, thus selecting the most effective forest site classification used for forest quality assessment. We first computed the mean biomass of each remnant old-growth forest community we had previously delimited, and then measured the within-class and between-class similarity of the mean biomass for each of the three classification schemes (Van Sickle, 1997). The most effective forest ecosystem classification should capture patterns of variability in forest biomass in remnant old-growth forest communities, where the dissimilarity of forest biomass between different communities (between-class) and similarity of forest biomass within the same community (within-class) should be precisely reflected. And it should meet the following requirements:

(i) within-class similarity in each class should be larger than its between-class similarity;

(ii) it should have the highest classification strength, i.e. it should have the greatest overall separation between the within-class and the between-class similarities.

A Bray-Curtis similarity measure (Ludwig & Reynolds, 2019) is used to calculate the percentage similarity between different remnant old-growth forest communities with similarity values ranging from 0 to 1. The forest biomass data for each remnant old-growth forest community was transformed using a Log(X + 1) function in order to use data with a normal distribution and homogeneity of variance in analysis.

The forest ecosystem classification strength is measured by calculating the average within-class similarity (w_i) for each of i classes and comparing the average within-class similarity for all classes ($\overline{W}$) with the average between-class similarities ($\overline{B}$). When the number of remnant old-growth forest communities in each class is unequal, $\overline{W}$ should be assessed by weighting w_i by the number of remnant old-growth forest community samples within each class (Snelder et al., 2004):

$$\overline{W} = \sum_{n=1}^{n} \left(\frac{n_i}{N}\right) w_i \tag{2}$$

where n_i is the number of remnant old-growth forest communities in class i and N is the total number of remnant old-growth forest communities in the Yangtze River Basin (Mielke, 1979). The statistics $\mathrm{M} = \overline{B}/\overline{W}$, and $\mathrm{CS} = \overline{W} - \overline{B}$ are used as descriptors of the overall classification strength. The value of M, an indicator reflecting separation between $\overline{W}$ and $\overline{B}$, lies between 0 and 1, and increases as classification strength increases. The value of CS is 0 if there is no class structure in the case and higher values indicate higher classification strength. A permutation test was established to validate the significance of the CS and M statistics in PRIMER 7.0 software based on the null hypothesis of no class structure (Van Sickle & Hughe, 2000). $\mathrm{P} < 0.05$ is used as the significance standard. The null hypothesis has more support as the value of CS approaches zero and M approaches one (Van Sickle, 1997).

A mean similarity dendrogram can effectively assess whether within-class similarity in each class is larger than its between-class similarities. It is composed of trees with nodes plotted with $\overline{B}$ as the abscissa axis and branch-ends for each class plotted atw_i. If the branch end is on the left side of the abscissa axis, it means within-class similarity in this class is smaller than between-class similarities. If the branch-end is on the right side of the abscissa axis, it means within-class similarity in this class is larger than between-class similarities. In the latter situation, a longer branch length indicates a higher classification strength for the class.

3.2.6. *Forest ecosystem quality assessment*

The mean biomass of the remnant old-growth forest sites in each forest site class is set as the local quality baseline. To validate the accuracy of local quality baseline estimation based on the RS approach, we used the data on remnant old-growth forest communities from field surveys at 114 sites to estimate the local quality baseline. The results showed that significant correlation was observed between the local biomass baseline obtained from field surveys and the RS estimation ($\mathrm{R}^2 = 0.81$, $\mathrm{P} < 0.01$).

A relative quality model was constructed to assess forest quality in each raster. The relative biomass density, the current forest biomass relative to the local remnant old-growth forest biomass, was chosen as the forest ecosystem quality index. The index is calculated as followed.

$$\mathrm{RQI} = \frac{B_i}{BB_i} \times 100\% \tag{3}$$

where RQI means relative quality index; B_i means the biomass of the forest ecosystem in pixel i, and BB_i means the local quality baseline in pixel i's forest site. Forest quality was classified into excellent, good, medium, low, and poor, in terms of $\mathrm{RQI} \geq 85\%$, $70 < \mathrm{RQI} < 85$, $50 < \mathrm{RQI} < 70$, $25 < \mathrm{RQI} < 50$, and $\mathrm{RQI} < 25$ (Dong et al., 2018), with set value of 5, 4, 3, 2, 1, respectively.

3.3. *Results*

3.3.1. *Test of the framework*

Based on the framework for forest ecosystem quality assessment (Fig. 1), the test of the framework mainly includes biomass retrieval, forest site classification selection, remnant old-growth forest delimitation and forest ecosystem quality assessment.

First, significant correlations were observed between the estimated remnant old-growth forests and field-observed biomass ($\mathrm{R}^2 = 0.84$, $P < 0.01$, $\mathrm{n} = 342$) (Fig. S1). The result indicates the accuracy of forest aboveground biomass estimation based on the RS approach.

Second, we tested the classification strength of three forest site classification methods. The results of mean similarity dendrogram analysis showed that all the branch-ends for all the classes in the first and the second forest site classification scheme are on the right side of the abscissa axis (blue line in Fig. 4(A) and (B)), indicating higher within-class similarity than between-class similarity. However, some branches of the third forest site classification are the on the left side of the abscissa axis (blue line in Fig. 4(C)), indicating that within-group similarity in those classes is lower than between-group similarity, which means the third classification scheme does not correctly reflect the forest biomass variation of remnant old-growth communities in the Yangtze River Basin. We further analyzed the classification strength indicators M and CS in each forest site classification and the result showed that the second forest site classification which considers vertical zonation has the highest classification strength ($\mathrm{CS} = 22.02$) (Table 1). Therefore, the second classification scheme meets the above requirements of the most effective forest site classification and was selected as the classification used for forest quality assessment.

Third, we used the stability of six forest groups with high biomass based on the trend in the median of the index from the top 30% to the top 5% (Fig. 5) to select the remnant old-growth forests. As shown in Fig. 5, the forest ecosystem stability index differs greatly initially (55.52 to 62.47 from the top 30% group to the top 15% group) and gradually become stable starting from the top 10% group (64.19 to 65.48 from top 10% group to top 5% group). Therefore, we chose the top 10% biomass group in native forest community of each protected area as the remnant old-growth forest community in Yangtze River Basin. The mean biomass of the remnant old-growth forest sites in each forest site class was set as the local quality baseline. We used the observed forest biomass data in remnant old-growth forests across all over the study area to test the accuracy of the forest quality baseline estimation based on our framework. The result shows that our framework produces highly accurate forest quality baseline estimations ($\mathrm{R}^2 = 0.81$, $\mathrm{n} = 114$). Compared to the accuracy validation of forest quality baseline estimation based on previous forest quality methods without the validation of classification effectiveness (Dong et al., 2018; Huang et al., 2020), our framework shows higher accuracy since the results accuracy of previous methods is relatively low ($\mathrm{R}^2 = 0.47$, $\mathrm{n} = 114$).

Finally, forest ecosystem quality changes were tested and we found that in 81.4% of the total area where new forests were planted due to the conversion of cropland to forests program (CCFP), the biomass stocking level increased in the years from 2000 to 2015 (Fig. 7). This indicates that the relative biomass stocking of forests is affected by restoration time.

3.3.2. *Forest quality pattern*

In this study, we used our framework to evaluate the forest quality in Yangtze River Basin. The forest quality assessment results show that good and medium level forests now only occupy 42.31% of the total forest extent, i.e. less than a half. Additionally, forest area of low and poor quality accounted for 34.46% of the total forest area in 2015 (Fig. 6, Table 2).

However, forest quality in the Yangtze River Basin increased greatly between 2000 and 2015. The areal proportions of forest of excellent and good quality increased by 18.99% and 8.03%, respectively (Table 2). Furthermore, the forest area increased by 1.71% between 2000 and 2015.

3.3.3. *Forest quality changes*

The regional forest quality assessment made between 2000 and 2015 (Fig. 7) demonstrates a huge improvement in forest quality. Nearly 55.72% of the forests in the basin improved their quality and the forest area increased by 1.71% due to afforestation projects. However, 7.07% of the forest area experienced ongoing degradation and 1.49% of the land area in the basin was deforested.

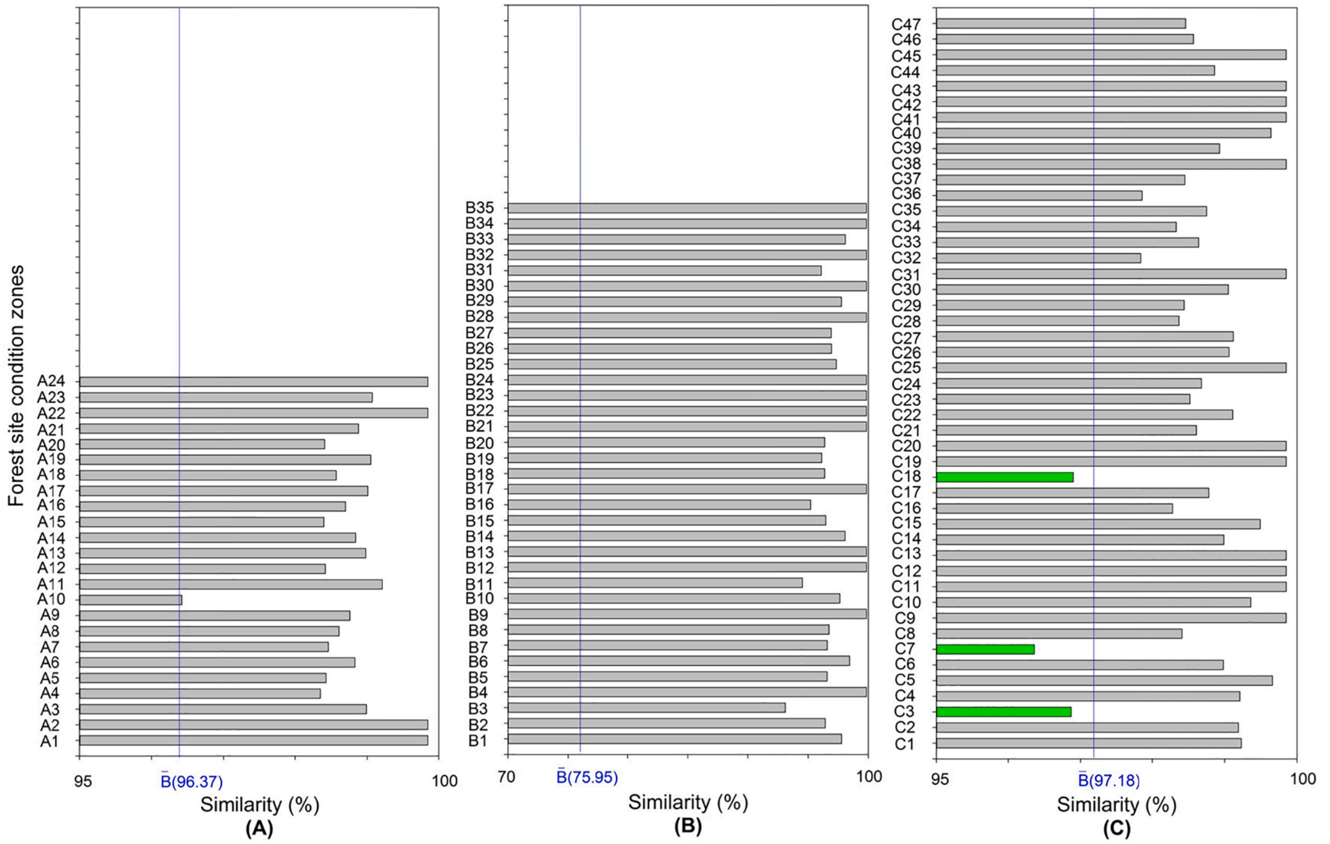

Fig. 4. Mean similarity dendrograms of the three forest site classification schemes: (a) traditional forest site classification considering accumulated temperature, precipitation and geomorphology, (b) revised forest site classification incorporating topography, and (c) revised forest site classification incorporating topography and soil attributes. (Note: the green bar in the dendrogram (C) indicates higher within-class similarity than between-class similarity). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
The classification effectiveness of different forest ecosystem classifications based on RS estimation data.

Classification type	Groups	$\overline{B}$(%)	$\overline{W}$(%)	M	CS
Traditional classification of the forest site system	24	96.37	98.84	0.98	2.24
Revised forest site classification with topography	35	75.95	97.97	0.78	22.02
Revised forest site classification with topography and soil	47	97.18	99.00	0.98	1.81

4. Discussion

Reversing the ongoing degradation of forest ecosystems requires timely and detailed monitoring of forest ecosystem extent and status. Because forest ecosystem processes increase in a stepwise fashion with restoration approaches (or decline due to human impacts), dynamic forest quality assessment can be made spatially explicit to inform about the current state of forest ecosystems and whether forest ecosystem quality has been ‘elevated’ or declined on the restoration staircase (Cramer et al., 2008; Chazdon, 2008). Although current forest quality assessments based on forest site classification provide an easily adaptable method for regional application, the uncertainty in accuracy and limitations in data collection make it difficult or impossible to apply at large scales. In this study, we provide an integrated framework which comprehensively considers improved forest site selection and remnant old-growth forest community delimitation. The framework includes the critical step of forest site classification effectiveness validation to ensure the selected classification effectively partitions within- and between-class forest quality variability. The RS approach based on vegetation naturalness and biological productivity stability analysis was developed for remnant old-growth forest community delimitation and proved to be appropriate for large-scale application while not demanding intensive

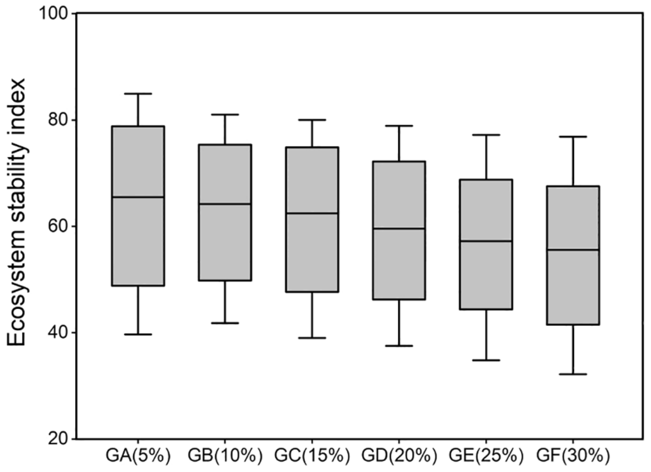

Fig. 5. The ecosystem stability index of different forest groups. Here, GA (group A), GB (group B), GC (group C), GD (group D), GE (group E), and GF (group F) mean areas with the top 5%, 10%, 15%, 20%, 25% and 30% of biomass.

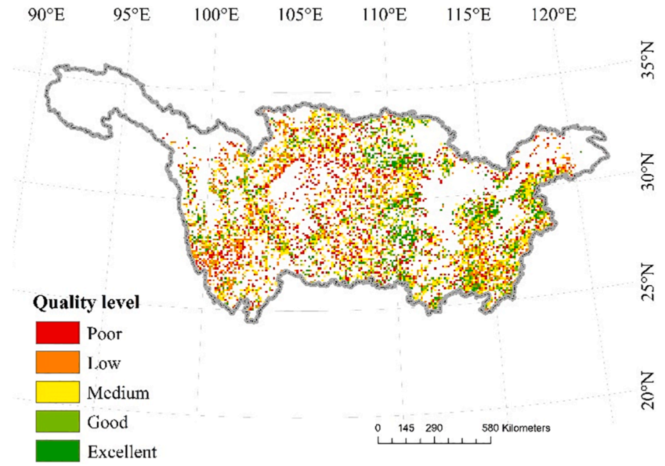

Fig. 6. The spatial pattern of forest quality in the Yangtze River Basin in 2015.

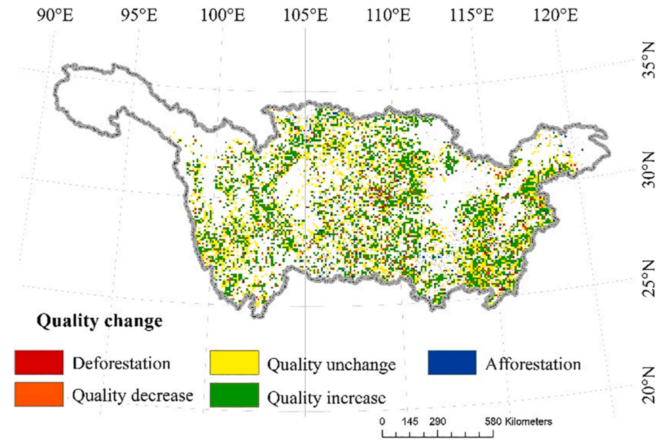

Fig. 7. The FEQI change in the Yangtze River Basin between 2000 and 2015 (Note: deforestation illustrates that the forest area decreased and afforestation illustrates that the forest area increased).

Table 2
The forest quality of the Yangtze River Basin in 2000 and 2015.

Quality level	2000 (%)	2015 (%)
Excellent	6.42	25.41
Good	8.87	16.90
Medium	24.58	23.23
Low	30.93	12.86
Poor	29.20	21.60

field data collection. Implementation of our framework considerably enhances the scope and detail of forest quality assessment, enabling better management of forest ecosystems.

The framework provides a new perspective for validation of the effectiveness of forest site classification selection. Previous studies used the interpretation of satellite imagery (Dong et al., 2018) or numerical classification based on abiotic environmental layers (Gao et al., 2010; Guo & Cui, 2014; He & Wang, 2013) to develop forest site classifications for regional forest quality assessment. While these methods have improved rapidity and adaptability for application, problems can arise if the congruence between the mapped forest site classification and the actual forest biological distributions are poor (Ferrier, 2002). We have used the observed forest biomass data of remnant old-growth forests to test the accuracy of previous forest quality methods without the validation of classification effectiveness (Dong et al., 2018; Huang et al., 2020). The result showed that the accuracy of forest quality baseline estimation is relatively low ($R^2 = 0.47$, $n = 114$). In this study, we set an effectiveness validation as a critical step and tested the effectiveness of different forest site classifications by classification strength analysis. The result of accuracy validation showed that our framework produced highly accurate forest quality baseline estimations ($R^2 = 0.81$, $n = 114$). Hence, by comparing the accuracy validation of these methods with our framework, we show that the accuracy of forest quality baseline estimation has been improved with the addition of forest site classification validation.

In this study, the second classification scheme included full consideration of climate, topography and the vertical distribution of forests and showed a higher classification strength than the other schemes. This indicates that vertical distribution is an important factor in determining forest distribution in the Yangtze River Basin and that forest quality in the high mountains may be underestimated where forest site classifications overlook the influence of vertical distribution. The third classification scheme further considered soil attributes and showed lower classification strength than the second scheme. A possible reason for this is that soil typology does not adequately describe soil chemical properties, which vary significantly with spatial heterogeneity within the same soil type (Sollins, 1998). However, soil chemical properties do show a significant relationship to forest biomass accumulation in the Yangtze River Basin (Zhang et al., 2015; Hui et al., 2014). What was demonstrated is that in this study soil features vary greatly within soil types and are not well described by the simple soil typology used. Hence, for this study forest site classification based on soil type did not reflect forest quality variation and cannot be used for accurate forest quality assessment. Perhaps other soil property factors instead of soil type used for forest site classification or the selection method is applied to other study area where soil type can well illustrate the difference in forest quality, the selection of proper forest site classification might be different. But it has been clearly proved that the validation of the effectiveness of forest site classification selection is essential for accurate forest quality assessment.

The framework can also provide a practical tool for rapid estimation of quality baseline data for forest quality assessment. For quality baseline estimation based on forest site classification, classic forest inventory approaches have been widely used (Czúcz et al., 2012; Xiao et al., 2016) to estimate the forest quality for timber management. Forest inventory data can provide sample data at large scales and accurate information on remnant old-growth forest communities. However, these approaches require large amounts of data and time-consuming data collection processes. For example, the periodicity for forest inventory in China is 5 years. Herein the forest inventory method cannot provide timely forest quality evaluation to guide forest restoration management. For large-scale forest restoration management, the lower requirements for forest biomass estimation accuracy compared to timber management (Guo et al., 2010) and the strong need for timely monitoring, which cannot be achieved by region-scale forest inventories (e.g., the forest inventories method used by Europe, the U.S., and others) (Czúcz et al., 2012; Woodall et al., 2011; Xiao et al., 2016), means RS-based forest quality estimation is a less costly choice than classical sample based field inventory. Some researchers have used RS methods to delimit remnant old-growth forests for large-scale application but recent research has not produced a rigorous approach for quality baseline estimation (Huang et al., 2020), potentially resulting in inaccurate forest quality assessments.

Since human impacts on the structure, composition or function of forests can affect forest quality, forests with high and stable biological productivity indicating no sign of logging or other destructive activities (Pflugmacher et al., 2014) and less change in plant species composition (Standish et al., 2014; Scholes and Biggs, 2005) can be selected as benchmarks for restoration management. In this study we used integrated indices, naturalness of vegetation and forest ecosystem stability, to select native forests with high biological productivity and stability as the reference sites for quality baseline estimation. In this study, we delimit 382 remnant old-growth forest communities in forest protected area in the Yangtze River Basin and use the mean biomass of the delimited remnant old-growth forest communities in each forest class as the local quality baseline for forest quality assessment (Table S3). The accuracy test of forest quality baseline estimation showed that the RS approach produced highly accurate local quality baseline estimations ($R^2 = 0.81$, $n = 114$). Therefore, the RS approach combined with available field data validation trialed in this study overcame the difficulty of data collection and may prove a reliable and convenient alternative for large scale application.

Our framework allows consistent (over time and between regions), comprehensive, and high-resolution analysis and reporting on forest ecosystem extent and status. It can facilitate efforts to plan, implement, monitor, and enforce forest management policies in terms of available spatial data in the regions where governments have responsibility for land use planning but lack spatial information (Hein et al., 2020). Firstly, the framework can help to predict the direction of future forest restoration management. Since dynamic regional forest quality assessment can reflect the status and trend of forest quality, both areas of forest degradation and those areas with low forest quality can be identified to allow policy makers to plan restoration programs. In this study, the extensive natural disturbance (due to effects such as debris flow or earthquakes in hilly areas) (Zhu et al., 2018; Liu et al., 2009) and human activities (such as urbanization and agriculture in the delta area) (Zhang et al., 2011) highly affected the forest quality and resulted in relatively low- and poor- quality forest. 34.46% of the forests in the Basin are of low or poor quality, primarily in the upstream mountainous areas and delta area (shown in Fig. 6). These areas have great potential for forest restoration to increase forest quality. Besides, human and natural disturbance between 2000 and 2015 still destroyed some forests and resulted in a decrease in forest area (deforestation area shown in Fig. 7) and forest quality (decreased quality area shown in Fig. 7) in some regions. 7.07% of the degraded forests occurred in the Sichuan Basin (middle area in the upstream section of the Yangtze River Basin) and the delta area (eastern part of the downstream section of the Yangtze River Basin). Forest degradation in the plain area where intensive human activities (Li et al., 2014) take place should receive more attention and forest restoration policies should consider economic development and environmental protection in this zone. Secondly, the framework can help to evaluate positive results from forest conservation management. From 2000 to 2015, the environmental protection program in some regions helped increase forest area and quality (quality increase and afforestation area shown in Fig. 7). 55.72% of the forest in the Yangtze River Basin showed quality improvement and 1.71% of the land was restored to forest. This indicates that forest restoration programs such as the Grain for Green Project and the Natural Forests Protection Project have made significant gains in restoring forest ecosystems towards self-supporting ecosystems resilient to perturbation without further intervention.

Our framework provides a relative precise evaluation of the forest quality status and trend in a large river basin to inform forest management. However, there are still some limitations on our framework. Some technical challenges remain, for instance, accounting for species and structural diversity, which are sensitive to human disturbance, into remnant old-growth forest community recognition at large scales remain challenging. Further study should embed indicators that reflect species turnover into quality baseline estimation for a more precise evaluation. Besides, the framework is still limited in identifying the specific driving force behind forest restoration and degradation at landscape scales. Generally, the longer the time since planting, the greater the biomass forests have. Relative stocking is simply a reflection of the time since tree planting (approaching a long-undisturbed maxima). In our study, we found that in 81.4% of the total area where new forests were planted due to the conversion of cropland to forests program (CCFP), the biomass stocking increased over a period of 15 years, indicating that the relative biomass stocking of forests is affected by the time since restoration was initiated. However, we need more detailed data to present the dynamics of the viability of the relative biomass indicators in light of forest age class and time since establishment. And our study can only illustrate the status and change pattern of forest quality to show where the forest quality increased or decreased. Further studies can develop more detailed approaches that recognize the factors influencing the status and changes in forest quality based on our results.

5. Conclusion

An improved framework was developed for regional forest ecosystem quality assessment. The framework integrated a more accurate forest site classification and forest biomass comparisons with homogeneous remnant old-growth forest communities. The most effective forest site could be selected by introducing a classification strength model. Large-scale remnant old-growth forest communities were delimited by introducing an RS-based method integrating species composition information and biological productivity characteristics recognition. By using the improved framework, forest ecosystem quality status, restoration potential and their dynamics were identified for the Yangtze River Basin, China. These assessment results provide important information on forest restoration management, including forest restoration potential and progress evaluation. The new forest quality assessment framework enhances the scope and accuracy of forest restoration information and can be applied as an evaluation tool for forest restoration management.

CRediT authorship contribution statement

Zhaowei Ding: Conceptualization, Formal analysis, Methodology, Validation, Writing - original draft, Writing - review & editing. **Ruonan Li:** Data curation, Formal analysis, Investigation, Validation, Writing - original draft, Writing - review & editing. **Patrick O'Connor:** Writing - original draft, Writing - review & editing. **Hua Zheng:** Conceptualization, Funding acquisition, Project administration, Writing - original draft, Writing - review & editing. **Binbin Huang:** Data curation, Formal analysis, Validation. **Lingqiao Kong:** Data curation, Formal analysis, Validation. **Yi Xiao:** Methodology, Writing - review & editing. **Weihua Xu:** Methodology, Writing - review & editing. **Zhiyun Ouyang:** Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.107370.

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