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Pattern and driver of *Rosa roxburghii* Tratt suitability and its effect on ecological services in karst desertification control areas

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Abstract

The eco-industry is an effective path to achieve ecological and economic sustainable development. However, the role played by *Rosa roxburghii* Tratt (*R. roxburghii*) industry in karst desertification control still needs to be determined. In this study, we predict the suitability probability and driving variables of *R. roxburghii*'s distribution through a Maximum Entropy model, combining climate, population, vegetation, and soil data, and conducted a sample plot survey in a high-suitability area to explore the role of the *R. roxburghii* industry in ecological services by using adjacent non-*R. roxburghii* patches as comparisons. The results showed that South China Karst, with its simultaneous rain and heat climate characteristics, was the most suitable area for the industrialization of *R. roxburghii* in the world. In South China Karst, the area of no, low, medium, and high suitability zones for *R. roxburghii* was 4.2×10^5 , 6.12×10^5 , 4.64×10^5 , and 4.42×10^5 km², respectively, and population distribution was the dominant variable controlling its distribution. The net primary productivity, soil conservation, water conservation, mean species abundance, and aboveground biomass of the *R. roxburghii* monoculture plot in the high-suitability area were significantly lower than those of adjacent non-*R. roxburghii* lands and forest patches. Furthermore, the monoculture had higher trade-offs between provision, regulation, and support service. This study found that the monoculture of *R. roxburghii* industry, dominated by human activities, failed to improve ecological services and exacerbated the trade-offs between services. Therefore, future karst desertification control still needs to follow the agroforestry development path.

Keywords *Rosa roxburghii* industry, Maximum entropy model, Service trade-off, Agroforestry

Introduction

Ecosystems and the services they provide underpin all aspects of human social [1, 2]. Many human economic and social developments have transcended several earth

boundaries in half a century [3]. The forest industry is an effective way to curb ecological degradation and improve service trade-offs, which is crucial for achieving a win–win between ecology and the economy [4]. In recent years, the development of the functional forest industry has been in full swing [5, 6], among which *Rosa roxburghii* Tratt (*R. roxburghii*) has attracted much attention due to its rich vitamin C content. It is reported that the vitamin C content of its fresh fruit is extremely high, ten times that of kiwifruit (*Actinidia chinensis* Planch), eighteen times that of Shatian pomelo (*Citrus maxima* (Burm.) Merr. cv. Shatian Yu), and fifty times that of sweet orange (*Citrus sinensis* (L.) Osbeck), respectively [7, 8]. In addition, *R. roxburghii* has an essential impact on disease resistance treatment and ecological services

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[9–11]. On the one hand, it has good health benefits for cancer prevention, anti-aging, atherosclerosis, hyperglycemia, and immunity enhancement [12–14]. On the other hand, agroforestry management of *R. roxburghii* helps to alleviate trade-off of ecological services [15] and improve the soil microbial structure and nitrogen content [16]. Therefore, *R. roxburghii* is particularly suitable for planting in areas caught in the ecological-impovertised trap.

In carbonate rock areas with severe soil erosion, ecological degradation triggered by population expansion has led to poverty by reducing agricultural income, and the current stage of ecological management eliminates the dilemma by introducing ecologically and economically balanced species. The higher the ratio of calcite to dolomite in areas dominated by carbonate rocks, the less residue is left to be dissolved. Therefore, it takes about 10,000 years to accumulate a 2.47 cm soil layer [17]. In addition, the binary structure exacerbates soil and water loss [18, 19]. These natural backgrounds dictate that the area has a weak land-carrying capacity and is drought-prone. Corn (*Zea mays* Linn. Sp) was introduced into China during the Jiajing period of the Ming Dynasty. Due to its drought tolerance and stable yield, it was widely planted in southern China [20]. During the Ming and Qing Dynasties, population expansion led to the expansion of maize cultivation on steep slopes, exacerbating land degradation and showing large areas of exposed bedrock [4]. In 1950, the dramatic increase in social production and population brought land degradation to a peak. As of 2021, the area of karst desertification in China is still 0.722×10^5 km², and the issues of land productivity loss and vegetation degradation have not been recovered [21]. To overcome this predicament, species that consider ecological and economic attributes have been introduced into karst desertification control [22, 23]. *R. roxburghii* has strong adaptability and high health benefits, which the government and farmers have favored. So far, the planting area of *R. roxburghii* in Guizhou is about 1.4×10^3 km², accounting for 0.8% of the provincial area. Despite the widespread cultivation of *R. roxburghii*, much of its research is limited to the microscopic scale.

Much research has been done on *R. roxburghii*'s effects on human health, but more is needed on its role as a pioneer species in controlling ecological degradation. Studies indicated that *R. roxburghii* industry in karst desertification areas was mainly based on a monoculture model, supplemented by *R. roxburghii* + *Juglans regia*, *R. roxburghii* + Leguminous forage [24]. The agroforestry model of *R. roxburghii* + arbor improved the fruit quality and ecological services compared to the monoculture, although its yields were affected. On the one hand, the contents of ascorbic acid, total

phenols, and saccharides in the fruits were significantly increased, and the content of Vc and manganese (Mn) in the fruit increased by 34.1% and 64.1% [16]. On the other hand, the content of total nitrogen, available nitrogen, and available potassium in the agroforestry model increased by 45.8%, 34.8%, and 67.8%, respectively; bacteria and fungi increased by more than 36.0%; potassium bacteria and nitrogen-fixing bacteria increased by 71.3% and 124.8% [16]. Nevertheless, these studies are still limited to the plot sample site scale and have yet to explore the pattern and driver of *R. roxburghii*'s suitability at the regional scale and their impacts on ecological services. At this stage, the maximum entropy model can enable the simulation of species' spatial distribution and explore the distribution drivers, providing an effective tool for research. It is mainly used for species distribution prediction under climate change [25], biodiversity conservation [26], and rural settlement site selection and planning [27]. However, there are no reports on using the maximum entropy model as a driving force analysis tool to establish a research framework for the pattern and driver of *R. roxburghii*'s suitability and its impact on ecological services.

Clarifying the spatial pattern and driver of *R. roxburghii* suitability is a prerequisite for understanding the ecological services provided by the *R. roxburghii* industry at this stage. Although agroforestry management of *R. roxburghii* contributes to realizing the Sustainable Development Goals (no poverty, zero hunger, decent work, and economic growth, climate action, and biodiversity), large-scale promotion still faces challenges due to the industry's profit-seeking nature [28]. From a producer perspective, agroforestry management significantly impacts fruit yield, seriously hindering economic returns. In fact, the ecological service improvement of agroforestry management comes at the cost of some fruit production, whereas farmers are not regularly compensated for this part of the loss [29]. Compensation usually occurs only at the beginning of planting and is given once according to the area or within a certain period, which may discourage farmers' enthusiasm for agroforestry management and gradually evolve into a monoculture model, especially in high-suitability areas. Although *R. roxburghii* still has high adaptability in land-degraded environments [22, 24], the monoculture model finds it challenging to achieve good ecological services supply capacity [16]. This study hypothesized that *R. roxburghii* in high-suitability areas would present a monoculture pattern, which may increase economic income [30] but is not conducive to improving ecological services and the relationship between services.

This study combined geographic data with field research to verify the above hypothesis by studying the pattern and driver of *R. roxburghii* suitability and its role in ecological services. First, climate data and the maximum entropy model were used to predict the suitability zones of *R. roxburghii* globally, identifying the most suitable areas as a case for the study. Second, climate, population, vegetation, and soil data were combined to further predict the probability and driver of *R. roxburghii* suitability in the South China Karst. Third, using the predicted probability data of *R. roxburghii* suitability, the suitable areas were divided spatially by thresholds. Within the designated high-suitability region, *R. roxburghii* plots were set up for field surveys. Adjacent non-*R. roxburghii* patches and forest patches were compared to explore the impact of *R. roxburghii* on ecological services.

Materials and methods

Study area

South China Karst (97°–117°E, 20°–35°N), including Yunnan, Guizhou, Guangxi, Sichuan, Hunan, Hubei, Guangdong, and Chongqing (Fig. 1), covers an area of about 1.938×10^6 km² [15]. Basins, hills, and mountains dominate the area, and the terrain decreases in elevation from northwest to southeast. The climate is mainly tropical and subtropical monsoon climate. The annual average temperature is about 14.40 °C, and the annual average precipitation is about 1194.37 mm. Precipitation

is concentrated mainly in summer, and the spatial pattern of rainfall gradually decreases from southeast to northwest. Soil types mainly include red, loess, lime, and purple soil. The interaction between the fragile ecological environment and excessive human activities has led to severe land degradation and serious vegetation destruction. In 2000, the implementation of Grain for Green promoted ecosystem restoration. From 2002 to 2017, aboveground carbon storage in the karst region of southern China increased by 0.11 ± 0.05 Pg C y⁻¹ [31]. On average, restored karst lands provided 29% and 18% higher biodiversity and ecosystem services than degraded karst lands [32]. Currently, this region has become a global greening hotspot [33].

Prediction of *R. roxburghii* distribution

Maxent settings

First, field surveys (Table S1) and the Global Biodiversity Information Facility (GBIF, <http://www.gbif.org>) were used to collect information on species coordinates. On a global scale, the bioclimatic variables in WorldClim (<https://www.worldclim.org>) were used as environmental factors (Table S2) to predict the suitability area of *R. roxburghii*. The aim was to verify that the South China Karst is the most suitable area for *R. roxburghii* globally and use it as a case study site. Further, population distribution, soil, digital elevation model, land cover, and climate data were used to finely predict the suitability of *R. roxburghii*

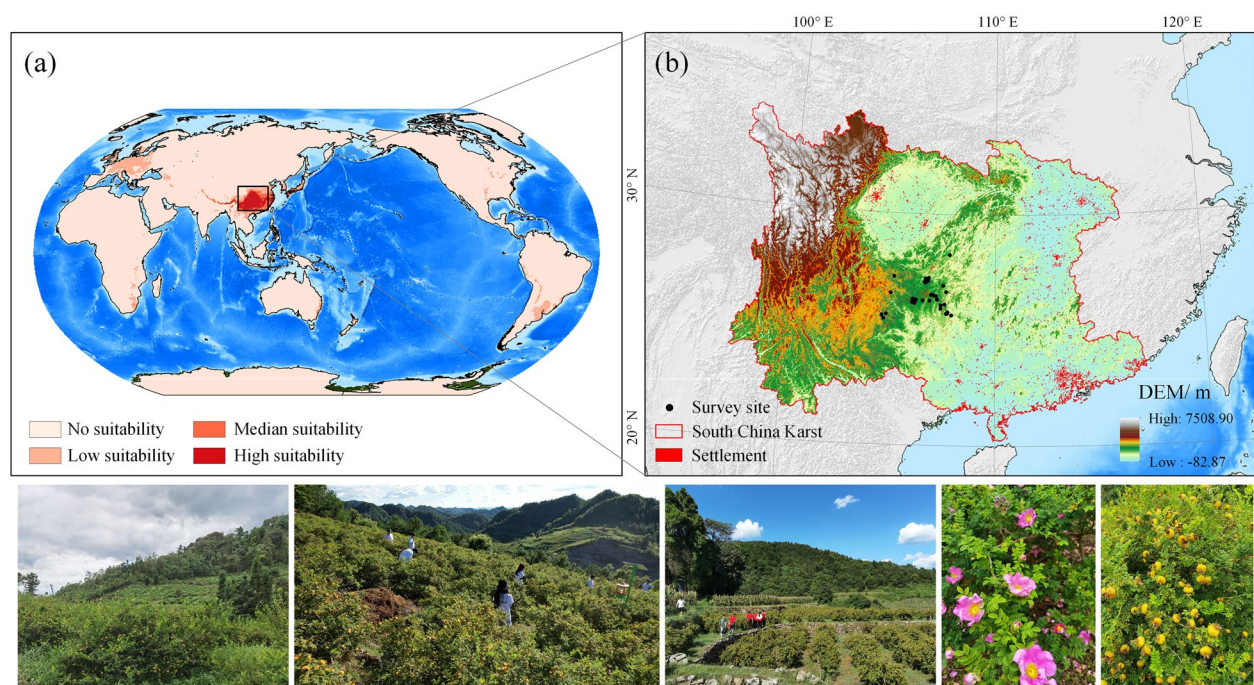


Fig. 1 Global suitability probability and case-site distribution of *R. roxburghii*

in South China Karst (Table 1). Second, correlation analysis was used to eliminate environmental variables with correlation coefficient greater than 0.8 to eliminate factor collinearity (Fig. 2). Third, *R. roxburghii* information and environmental data were input into the species distribution and environmental variable module. 75% of the distribution points were randomly selected as the training data set for model building, while the others were used as the test data set for model verification. The model control ratio, maximum number of iterations, and convergence threshold remain default. Fourth, ten bootstrap replications were conducted and set up to plot response

Table 1 Environmental variables required by Maxent model in South China Karst

Variable	Data source	Resolution	Related model
Bulk density (BD)	Mapping high-resolution National Soil Information Grids of China by Liu et al. [34]	1000 m × 1000 m	Maxent
Coarse_fragment (CF)		1000 m × 1000 m	Maxent
Soil thickness (ST)		1000 m × 1000 m	Maxent
Digital Elevation Model (DEM)	NASA SRTM Digital Elevation, https://cmr.earthdata.nasa.gov/	30 m × 30 m	Maxent
Bioclimatic variables	WorldClim, https://www.worldclim.org/	1000 m × 1000 m	Maxent
Population (POP)	WorldPop, https://www.worldpop.org/	100 m × 100 m	Maxent
Normalized Difference Vegetation Index (NDVI)	MODIS Global NDVI and AVHRR NDVI https://lpdaac.usgs.gov/products/mod13q1v006	250 m × 250 m	Maxent
Land cover (LC)	Annual China Land Cover Dataset https://essd.copernicus.org/articles/13/3907/2021/	30 m × 30 m	Maxent

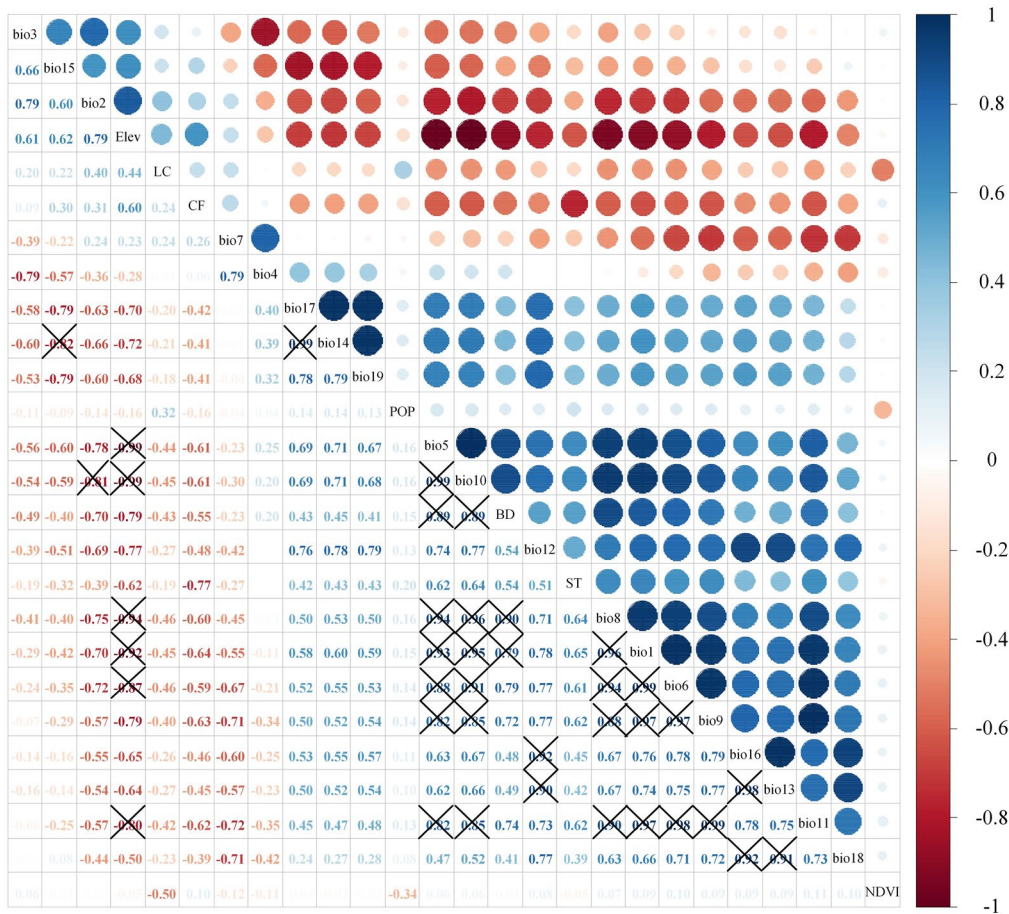


Fig. 2 Correlation analysis of bioclimatic factors in South China Karst

curves to evaluate model accuracy. The Jackknife analysis included with the model was used to determine the contribution rate of variables affecting the suitability of *R. roxburghii*.

Suitable areas division

Model validation is a prerequisite for ensuring the accuracy of the prediction results and the division of suitable areas, so this study used the ROC (receiver operating characteristic)-AUC (area under the curve) method to test the prediction results of the model. The ROC curve is a graph generated by the actual positive value (sensitivity) on the x-axis and the false positive value (1-feature) on the y-axis at different thresholds (or cutoff points). As the sensitivity increases, the false positive results will also increase [35]. The area enclosed by the ROC and the abscissa is the AUC value, and its size is used to reflect the accuracy of the prediction result. AUC takes values between 0 and 1, with larger values indicating better model predictions. ROC less than 0.6 is unqualified, 0.6–0.7 is poor, 0.7–0.8 is fair, 0.8–0.9 is good, and greater than 0.9 is excellent. In this study, if the model ROC results were higher than 0.8, the predicted data were categorized using the quantile method in ArcGIS, and the data were classified into four types (no suitable, low suitable, median suitable, and high suitable area) (Table 2). ArcGIS and geographic information systems are essential tools for processing, analyzing, and visualizing geographic data, so they were used to divide suitable regions in this study [36, 37].

Ecological service assessment

The suitability of *R. roxburghii* was first quantified to clarify the spatial pattern of *R. roxburghii* and its role in ecological restoration. Second, 43 *R. roxburghii* distribution sites were randomly surveyed within the highly suitable areas and compared with adjacent non-*R. roxburghii* and forest patches to explore the relationship between *R. roxburghii* and ecological services. The supplementary material (Figs. S1, S2) illustrates the selection method for adjacent non-*R. roxburghii* and forest patches. It should be noted that the ecological services data quantified in this study are all from 2020 because we cannot guarantee that these survey sites were *R. roxburghii* before that

time. Table 3 lists the data and information sources used to quantify ecological services.

Water conservation (WC)

Water conservation was calculated using the Intelligent Urban Ecosystem Management System (IUEMS, <https://www.iuems.com/eco/index.html>) model. This module was mainly calculated by precipitation, evapotranspiration, and runoff. The formula was as follows:

$$WC = P_i - R_i - ET_i \quad (1)$$

where: WC was water conservation. P_i , R_i , and ET_i were annual precipitation (mm), runoff (mm), and evapotranspiration in each grid i , respectively.

Net primary productivity (NPP)

Using the Carnegie-Ames-Stanford approach model to calculate net primary productivity, simulation results of $\varepsilon_{\max}$ of typical vegetation types in China by Zhu et al. [39] were referred to. NPP was calculated from NDVI, temperature, precipitation, solar radiation, and land cover data. The formula was as follows:

$$NPP(x, t) = APAR(x, t) \times \varepsilon(x, t) \quad (2)$$

where: NPP, $APAR(x, t)$, and $\varepsilon(x, t)$ were the net primary productivity ($\text{gC m}^{-2} \text{yr}^{-1}$), the photosynthetic effective radiation (MJ m^{-2}) absorbed by vegetation at grid x in month t , and the actual light energy utilization rate, respectively.

Soil conservation (SC)

Previous models may have overestimated rainfall erosion in South China Karst, so we estimated soil retention using the assessment method of Li et al. [40]. The assessment results of this method have good effects in the karst region. The formula was as follows:

$$SC = R \times K \times LS \times (1 - C \times P) \quad (3)$$

where: SC, R , K , L , and S were soil conservation ($\text{t ha}^{-1} \text{yr}^{-1}$), the rainfall erosivity factor ($\text{MJ mm hr}^{-1} \text{ha}^{-1} \text{yr}^{-1}$), soil erodibility factor ($\text{t hr ha ha}^{-1} \text{MJ}^{-1} \text{mm}^{-1}$), the slope length, and slope factor, respectively. C and P were the vegetation coverage factor and conservation measure factor.

Soil nutrient index (SNI)

Mapping high-resolution National Soil Information Grids of China by Liu et al. [34]. was used to establish the soil nutrient index model. This module was mainly calculated by soil organic carbon, total nitrogen, total phosphorus, and total potassium. The formula is as follows:

Table 2 Threshold classification of suitable areas

Classification	Threshold
No suitable area	0–0.0039
Low suitable area	0.0040–0.0314
Median suitable area	0.00315–0.1216
High suitable area	0.1217–1

Table 3 The data used for ecological service assessment

Indicator	Data source	Resolution	Related model
Land cover	Annual China Land Cover Dataset, https://essd.copernicus.org/articles/13/3907/2021/	30 m × 30 m	Soil conservation, Water conservation, Net primary productivity, Mean species abundance
Temperature	China Meteorological Data Center, http://data.cma.cn/	500 m × 500 m	Net primary productivity
Precipitation	China Meteorological Data Center, http://data.cma.cn/	500 m × 500 m	Net primary productivity, Soil conservation, Water conservation
Rainfall erosivity	China Meteorological Data Center, http://data.cma.cn/	500 m × 500 m	Soil conservation
Soil erodibility	Calculated by HWSD v1.2, https://data.tpdc.ac.cn	1000 m × 1000 m	Soil conservation
Solar radiation	WorldClim, CHELSA, https://www.worldclim.org/	1000 m × 1000 m	Net primary productivity
NDVI	MODIS Global NDVI and AVHRR NDVI, https://lpdaac.usgs.gov/products/mod13q1v006	250 m × 250 m	Net primary productivity, Soil conservation, Maxent
DEM	NASA SRTM Digital Elevation, https://cmr.earthdata.nasa.gov/	30 m × 30 m	Soil conservation, Maxent
Evapotranspiration	Penman–Monteith–Leuning Evapotranspiration V2, https://github.com/gee-hydro/gee_PML	500 m × 500 m	Water conservation
Soil organic carbon Total nitrogen Total phosphorus Total potassium	Mapping high-resolution National Soil Information Grids of China by Liu et al. [34]	1000 m × 1000 m	Soil nutrient index
Aboveground biomass carbon	Maps with 1 km resolution reveal increases in above- and belowground forest biomass carbon pools in China over the past 20 years by Chen et al. [38]	1000 m × 1000 m	Provision service index

$$SNI = (Z_{SOC} + Z_{TN} + Z_{TP} + Z_{TK})/4 \quad (4)$$

where: SNI is the soil nutrient index. Z_{SOC} , Z_{TN} , Z_{TP} , and Z_{TK} were standardized soil organic carbon, standardized total nitrogen, standardized total phosphorus, and standardized total potassium, respectively.

Mean species abundance (MSA)

Referring to the method of Schipper et al. [41], mean species abundance was quantified.

Provision service index (PSI)

Maps with 1 km resolution reveal increases in above and belowground forest biomass carbon pools in China over the past 20 years by Chen et al. [38] was used to establish the provision service index model. Above-ground biomass is a supply service that can be characterized as wood supply. The formula is as follows:

$$PSI = Z_{AGB} \quad (5)$$

where: PSI was provisioning service index. Z_{AGB} was standardized above-ground biomass carbon (tC ha^{-1}).

Regulation service index (RSI)

$$RSI = (Z_{NPP} + Z_{SC} + Z_{WC})/3 \quad (6)$$

where: RSI was the regulating service index. Z_{NPP} , Z_{SC} , and Z_{WC} were standardized net primary productivity, standardized soil conservation, and standardized water conservation, respectively.

Support service index (SSI)

$$SSI = (Z_{SNI} + Z_{MSA})/2 \quad (7)$$

where: SSI was supporting service index. Z_{SNI} and Z_{MSA} were standardized soil nutrient index and standardized mean species abundance.

Ecological service supply capacity (ESSC)

Ecological service supply capacity was obtained by summing the indicators of provision service, regulation service, and support service and then calculating the mean value.

$$ESSC = (Z_{AGB} + Z_{NPP} + Z_{SC} + Z_{WC} + Z_{SNI} + Z_{MSA})/6 \quad (8)$$

Statistical analysis

This study first used the Maxent model to quantify the spatial distribution of *R. roxburghii* suitability worldwide using geographical coordinates and bioclimatic variables as input factors. Second, fine-scale prediction of *R. roxburghii* suitability was carried out in South China Karst by combining climate, soil, topography, population, and vegetation factors, and Jackknife quantified the contribution of these factors to *R. roxburghii* suitability. Third, the suitability of *R. roxburghii* was graded using the threshold-based quantile method in ArcGIS. Fourth, structural surveys and location coordinates of the *R. roxburghii* sample plots were conducted in highly suitable areas, and quantified ecological service data of the *R. roxburghii* sample plots were extracted through ArcGIS. Finally, the data were similarly extracted from the adjacent non-*R. roxburghii* and forest patches to the survey sites, and Kruskal–Wallis and correlation analyses were used to compare the differences in services and the trade-offs between services.

Results

Prediction of *R. roxburghii* suitability

Bioclimatic data predicted the global suitability of *R. roxburghii* and the results showed that the medium and high-suitable distribution of *R. roxburghii* were mainly concentrated in southern China Karst (Fig. 1a). The low suitable areas were primarily concentrated in central and western Europe (UK, France, Germany, Italy, Poland, Czech Republic, Austria) and South America (Uruguay, Argentina). This information indicated that South China Karst is the most suitable area for the industrialization of *R. roxburghii*. From a global perspective, the dominant factors affecting the suitability of *R. roxburghii* were the mean temperature of driest quarter (bio9), the min temperature of coldest month (bio6), and the precipitation of warmest quarter (bio18) (Fig. 3a). The study believes a probability greater than 0.5 is the most favorable growth range for species [42]. From the single factor response curve, it can be seen that the optimal growth range of *R. roxburghii* in the mean temperature of driest quarter (bio9) is 3–11 °C (Fig. 3b), the optimal growth range of the lowest temperature in the min temperature of coldest month (bio6) is –4–4.5 °C (Fig. 3c), and the optimal

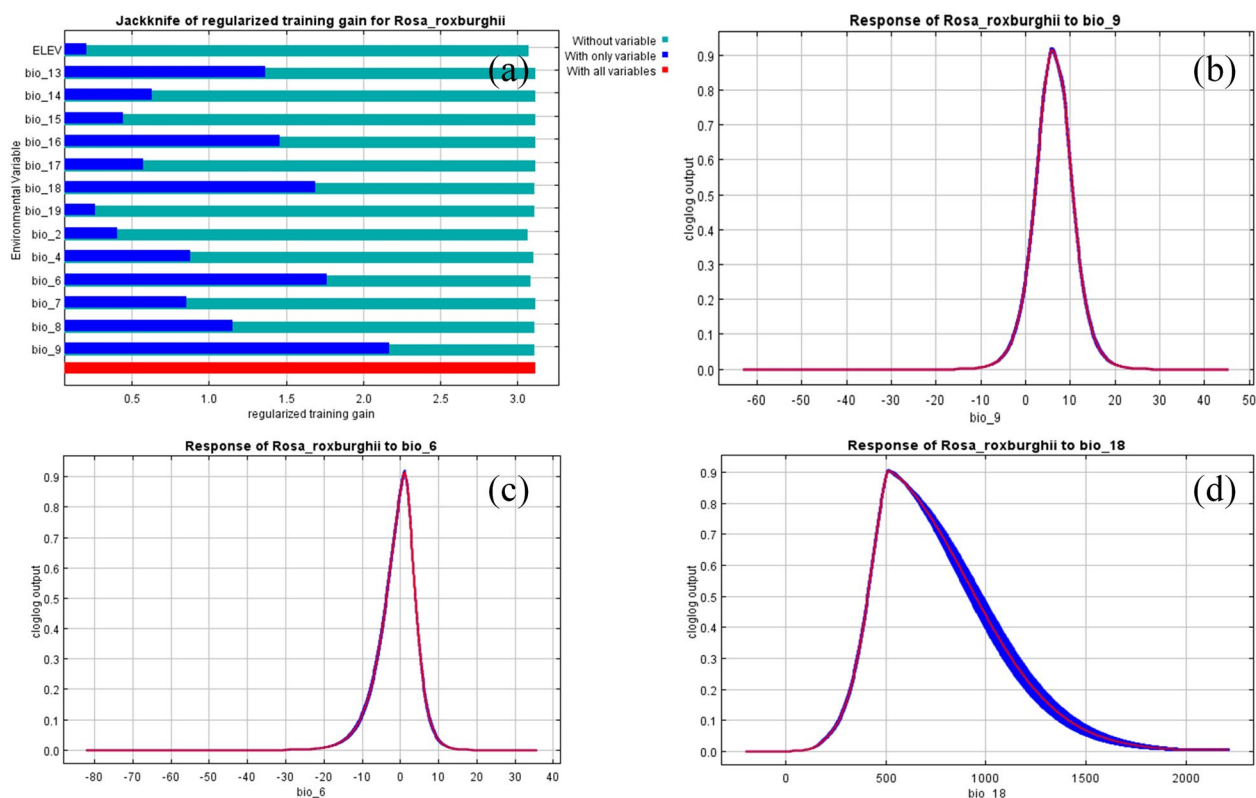


Fig. 3 Driving factors and thresholds of *R. roxburghii* suitability at the global scale. **a** Driving factors of *R. roxburghii* suitability, **b, c, d** the responses of bio9, bio6 and bio18 to *R. roxburghii* suitability, respectively

growth range of precipitation in the precipitation of warmest quarter (bi18) is 400–950 mm (Fig. 3d).

Combining factors such as climate, soil, topography, population, and vegetation, a detailed prediction of *R. roxburghii*'s suitability in South China Karst was conducted. The results showed that the no-suitable, low-suitable, medium-suitable, and high-suitable areas were $4.2 \times 10^5 \text{ km}^2$, $6.12 \times 10^5 \text{ km}^2$, $4.64 \times 10^5 \text{ km}^2$, and $4.42 \times 10^5 \text{ km}^2$, respectively. (Fig. 4a). Spatially, the high suitability areas of *R. roxburghii* were mainly distributed in Guizhou, Chongqing, eastern Sichuan, and west Yunnan; the medium suitability areas were primarily

distributed in north Yunnan, the Sichuan Basin, and south Sichuan; the low suitability areas were mainly distributed in Hubei, central Yunnan, north Sichuan, and west and south Hunan; the rest were no suitable areas (Fig. 4b). From the perspective of the administrative regions, Guizhou has the most significant proportion of medium and high-suitable areas, accounting for 99.73% of the regional area. Chongqing accounted for 94.09%. The data analysis reveals that Guizhou and Chongqing have great potential in developing *R. roxburghii* industry. Yunnan, Sichuan, Hubei, Hunan, Guangxi, and Guangdong accounted for 57.08%, 49.92%, 41.00%, 24.31%, 24.55%, and 2.24%, respectively (Fig. 4c). The average temperature, precipitation, and diurnal temperature difference of the median and high-suitable area in South China Karst were 1.20–22.85 °C, 491–2722 mm, and 4.95–14.55 °C, respectively, indicating that the warm climate, sufficient rainfall, and moderate daily temperature range provide suitable ecological environments for the growth of *R. roxburghii*.

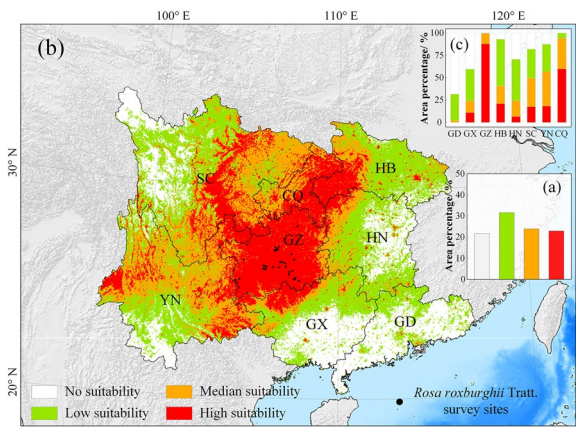


Fig. 4 Distribution of the suitable area of *R. roxburghii*. **a** Proportion of different suitable regions; **b** Distribution of suitable regions. **c** Percentage of different suitable areas in the administrative area. GD, GX, GZ, HB, HN, SC, YN, and CQ are Guangdong, Guangxi, Guizhou, Hubei, Hunan, Sichuan, Yunnan, and Chongqing, respectively

Variables influencing the suitability of *R. Roxburghii*

The area under the curve evaluated the prediction results, which showed that AUC was more significant than 0.943, indicating good prediction results (Fig. 5a). Among the environmental factors, Jackknife analysis results exhibited that population distribution, land cover, Bio9 (average temperature in the driest season), and DEM were the dominant variables affecting the suitability of *R. roxburghii* (Fig. 5b). Combined with the investigation of 43 survey sites in Guizhou (Table S1),

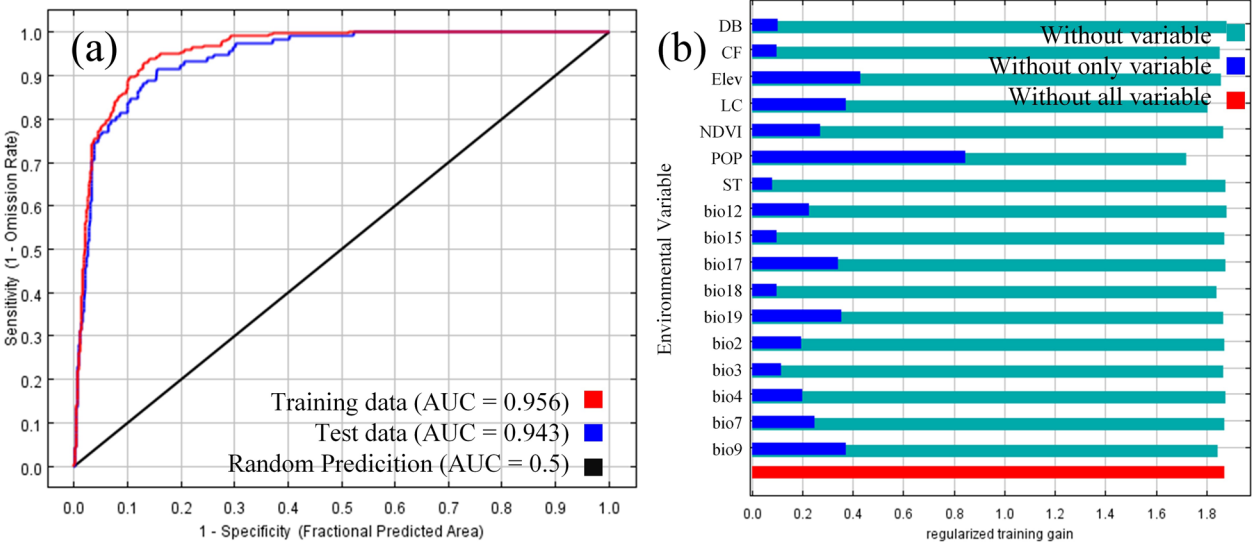


Fig. 5 *R. roxburghii* suitability evaluation and influencing variables. **a** Evaluation simulation results. **b** Contribution rate to driving factors

it was found that these sites were all monoculture, and all were distributed in high-suitability areas. According to the AUC evaluation results and field verification, our prediction results aligned more with objective laws.

Ecological service characteristics of *R. roxburghii*

Ecological service characteristics of *R. roxburghii* and adjacent non-*R. roxburghii* and forest patches were quantified to investigate *R. roxburghii*'s role in ecological services. The results showed that in addition to soil nutrient index (SNI), net primary productivity (NPP), soil conservation (SC), water conservation (WC), mean species abundance (MSA), and above-ground biomass (AGB) of the adjacent non-*R. roxburghii* land was higher than those of the monoculture. NPP, SC, WC, MSA, and AGB of the adjacent non-*R. roxburghii* land was 3.69%, 10.84%, 2.33%, 2.41%, and 10.54% higher than monoculture *R. roxburghii* land, respectively (Figs. 6, 7). Furthermore, we compared the adjacent forest patch with *R. roxburghii* sites, and the results revealed that the former's NPP, SC, WC, SNI, MSA, and AGB were 16.86%, 45.15%, 2.21%, 0.09%, 24.89%, and 73.69% higher than those of the latter, respectively. These findings demonstrated that adjacent non-*R. roxburghii* land and adjacent forests are superior to *R. roxburghii* monocultures for ecosystem

carbon sequestration, soil, and water loss, and biodiversity enhancement. In conclusion, *R. roxburghii* monoculture may not improve ecological services in ecologically degraded areas but may exacerbate the deterioration.

The provision service index, regulation services index, support services index, and ecological service supply capacity after weighted average processing were subjected to a one-way analysis of variance. The results displayed that adjacent non-*R. roxburghii* lands of these four indexes were higher than those of the monoculture. The former's provision service index, regulation services index, support services index, and ecological service supply capacity were 10.84%, 6.22%, 6.30%, and 5.02% higher than the latter, respectively. Moreover, the results also exhibited that the provision service index, regulation service index, support service index, and ecological service supply capacity of adjacent forest patches were higher than that of *R. roxburghii* sites by 83.34%, 16.49%, 7.52%, and 28.02%, respectively (Fig. 8a–d). This information further corroborates the impact of the monoculture model on ecological services.

Further, we evaluated the relationship of three indices between the monoculture and the adjacent non-*R. roxburghii* land. The results manifested that although the regulation service index and the support service index

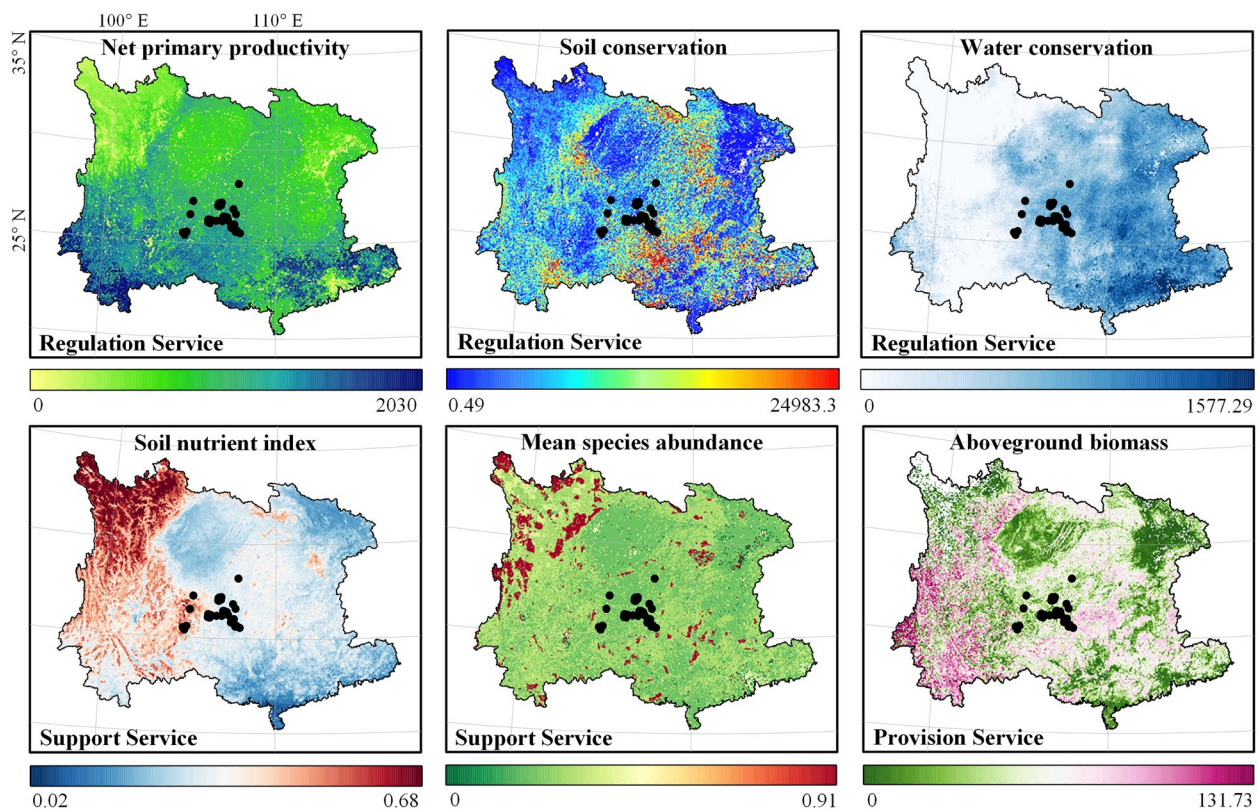


Fig. 6 Characteristics of ecological services in South China Karst

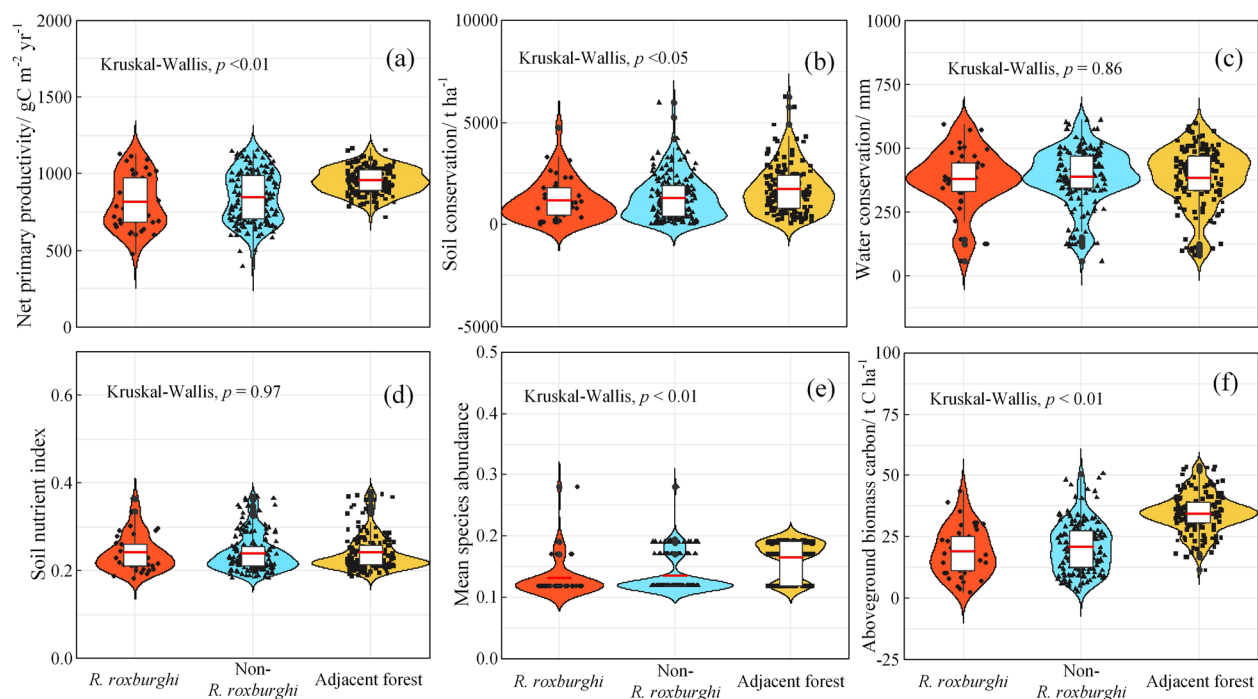


Fig. 7 Ecological service differences among different research study units

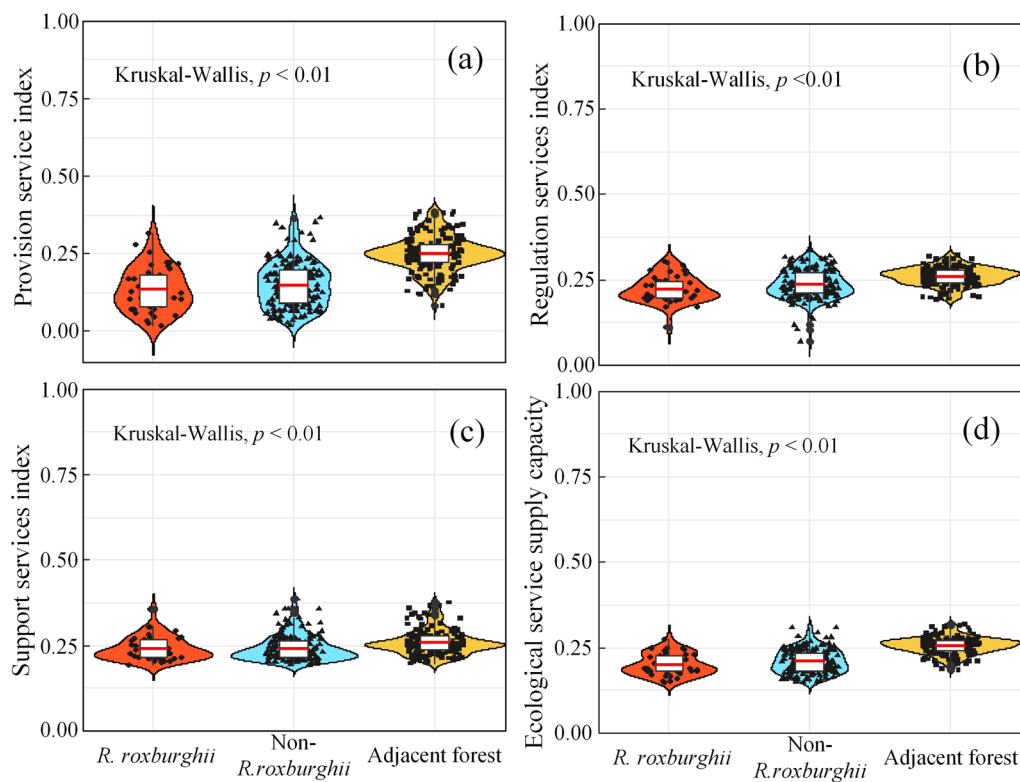


Fig. 8 Ecological service differences between adjacent patches of non-*R. roxburghii* land and adjacent forest patches with monoculture

showed positive correlations with the provision service index in both land use, the synergy of adjacent non-*R. roxburghii* lands were higher than the monoculture and showed a significant relationship ($p < 0.05$). In the support services and the regulation services index, although there is a very significant negative correlation between the indices of the two land use ($p < 0.01$), the trade-off relationship of the latter was significantly better than that of the former (Fig. 9). These results indicated that the monoculture of *R. roxburghii* not only failed to improve ecological services but also significantly exacerbated the trade-off relationship between services.

Discussion

Distribution and controlling variables of *R. Roxburghii*

This study divided the spatial pattern and determined the driver of *R. roxburghii* suitability by establishing comprehensive and large-scale geographic information data of *R. roxburghii*. Bioclimatic data were used on a global scale to predict the probability of *R. roxburghii* suitability, and the results showed that South China Karst is the most suitable area for *R. roxburghii* in the world. Based on Jackknife's contribution analysis, the mean temperature of the driest quarter, the minimum temperature of the coldest month, and the precipitation of the warmest quarter

were the dominant variables controlling the suitability of *R. roxburghii* at the macro-scale. The combination of climate, population, vegetation, and soil data further predicted suitable areas in South China Karst, indicating that population distribution, land cover, mean temperature of the driest quarter, and DEM were the dominant variables controlling the suitability at the local scale. From the perspective of natural factors, the combination of temperature and precipitation played a decisive role in the suitability of *R. roxburghii*. The climate characteristics of the same period of rain and heat from June to August (precipitation accounts for 48.05% of the whole year, and the average daily temperature is 22.52°C) are the congenital conditions for the growth of *R. roxburghii* in South China Karst. From the human perspective, population distribution was a dominant variable for *R. roxburghii* suitability at the local scale. Moreover, the two are spatially coupled, which suggests that *R. roxburghii* is largely anthropogenically cultivated in South China Karst.

The government's confidence in curbing land degradation and farmers' determination to escape from poverty drove the large-scale promotion and cultivation of *R. roxburghii* [15], both of which contributed to its wide distribution. Overlaying carbonate rocks with *R. roxburghii* suitable areas, 66.47% of carbonate rocks in South China

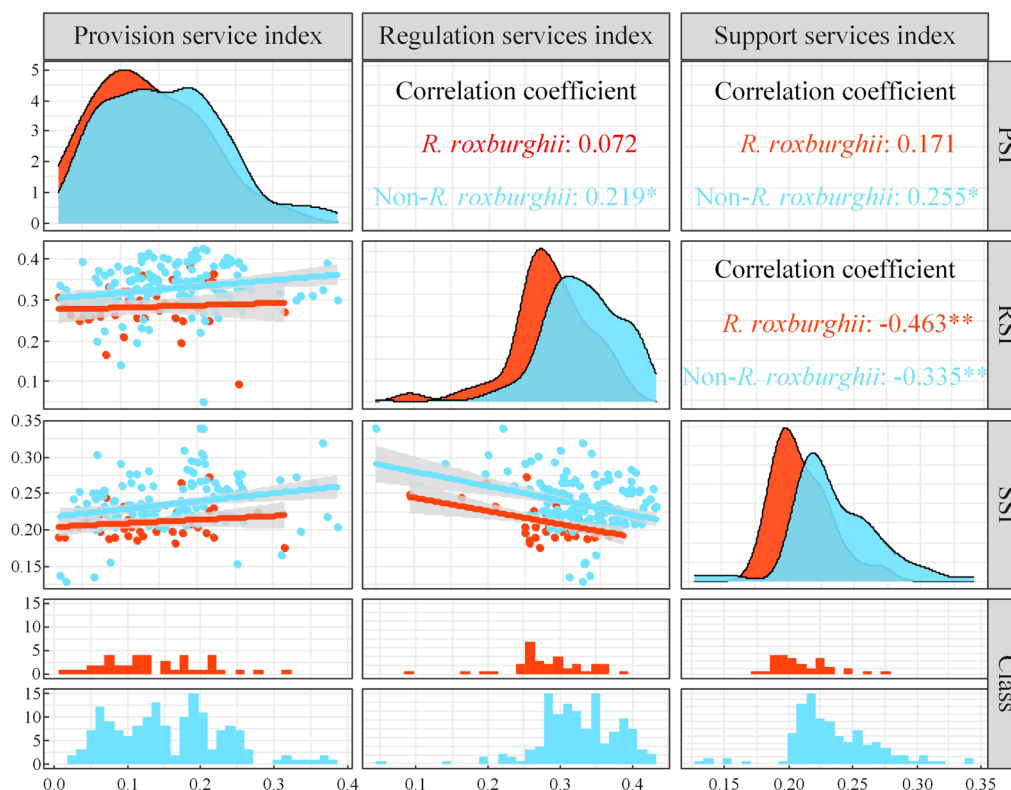


Fig. 9 Relationship between provision, regulation, and support service

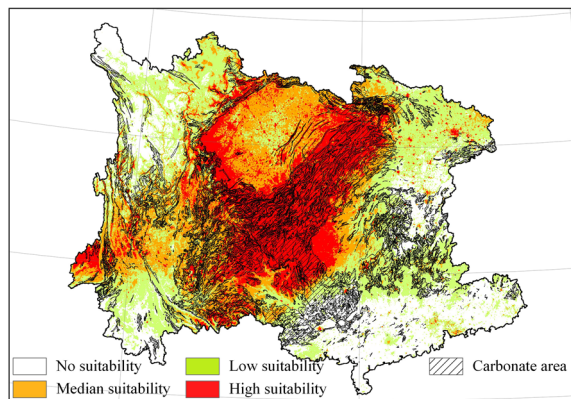


Fig. 10 Suitability area of *Rosa roxburghii* and distribution of carbonate rocks

Karst were distributed in medium and high-suitable areas (Fig. 10). This phenomenon is explained by the fact that *R. roxburghii* does not require high soil quality and has the potential to be exploited for its unique value [14], which determines that it is well suited to be grown in carbonate rock areas. In contribution rate analysis, population distribution was the dominant variable affecting the suitability of *R. roxburghii* (Fig. 5b). This information can help us corroborate that it was not surprising that *R. roxburghii* was widely distributed in degraded or vulnerable areas because the government and farmers had a consistent demand. We also validated the predicted results by 43 survey sites, demonstrating that all presented monoculture models had good growth conditions (Fig. 1). In conclusion, our prediction of the suitability of *R. roxburghii* was consistent with the objective law.

The relationship between *R. roxburghii* and ecological services

Within the high suitability area quantified by the Maxent model, we randomly surveyed 43 *R. roxburghii* sites, which showed a monoculture model. In fact, the agroforestry model was the most effective practice of ecological management through biological measures [43]. For example, an agroforestry model of *R. roxburghii* + *Juglans regia* + herbage was used for ecological restoration in the karst desertification control area of Bijie, China. Compared with the monoculture model, the study effectively mitigated the trade-off of ecological services through agroforestry [15]. However, the existing *R. roxburghii* planting structure is far from the planting structure that can improve ecological degradation, which may be closely related to the ecological compensation policy and farmers' needs. At present, China's ecological compensation policy is mainly divided into two categories. One category compensates farmers according to the area of Grain

for Green, and the other gives subsidy payments based on the number of plants [33]. Anyway, almost all of these ecological subsidies occurred at the initial stage of land conversion, insufficient to compensate for the loss of land conversion [29]. Additionally, the agroforestry model was considered to have good synergy between ecology and economy, but this model required higher maintenance costs. The premise of symbiosis among plants was that they need to occupy ecological niches with differences, so pruning, shaping, controlling planting density, and fertilizing required more effort than monoculture. Most importantly, farmers' ultimate aim in developing forest industries is to have higher returns [28], coupled with the environmental conditions in highly suitable areas that contribute to the widespread cultivation of *R. roxburghii*. Driven by these conditions and background, the initial agroforestry model was transformed into the current monoculture.

By comparing with adjacent patches of non-*R. roxburghii* and adjacent forest patches, *R. roxburghii* monoculture failed to improve ecological services in degraded or vulnerable areas, exacerbating the trade-off between services. Ecosystem multifunctionality tends to have positive feedback with the abundance of species occupying different ecological niches [44], demonstrating that monoculture models deteriorated ecological services. Studies have shown that increased land use intensity can cause a reduction in the ecological niche differentiation of species in communities, leading to significant degradation of soil and water conservation [45, 46]. Our study also showed that carbon sequestration, soil and water conservation, and biodiversity of *R. roxburghii* monoculture were significantly lower than those of adjacent non-*R. roxburghii* land and adjacent forest patches (Fig. 7), consistent with previous findings. However, the soil nutrient of the monoculture was slightly higher than that of the adjacent non-*R. roxburghii* land, which may be related to the fact that plant communities with higher species abundance would absorb more soil nutrients. Although *R. roxburghii* monoculture can harvest, in general, more fruit yield and increase economic returns at this stage, long-term cultivation would exacerbate land productivity degradation. Eventually, farmers will gradually abandon planting due to the high input and low return caused by degraded land [47].

This study results may be supplementary to the existing understanding of the forest industry. We found that reduced agricultural incomes and inadequate ecological compensation drive farmers to shift from agroforestry (ecological-economic type) to monoculture (economic type), which led to a deterioration of ecological services and increased trade-offs between services. Initially, the widespread promotion and cultivation of *R. roxburghii*

were driven by both government and farmers. On the one hand, the government initially intended to curb ecological degradation and help achieve sustainable development through Grain for Green [48]. On the other hand, farmers were willing to plant *R. roxburghii* because of its good suitability and higher economic value than food crops. However, declining agricultural returns and insufficient ecological compensation drove farmers to choose the monoculture model after reforestation. In the short term, monoculture can make up and enhance the economic return, but long-term planting will deteriorate the ecological services in the degraded ecoregion. Our study emphasized that the development of the forest industry in degraded ecoregions needs to focus on the planting structure. Otherwise, large-scale monoculture may not necessarily achieve a win–win situation. The effectiveness of agroforestry management has been widely verified in land resource-scarce and degraded ecoregions [43]. Therefore, the agroforestry model should be the focus of the next stage of forest industry development in karst desertification areas.

Limitations

In this study, information on the coordinates of *R. roxburghii* was collected through the GBIF website, published papers, and field surveys, but there may still be a slight bias in the prediction results because of insufficient sample sites. However, we verified the results using 43 sample sites in Guizhou and explained why the medium–high suitable area of *R. roxburghii* was heavily distributed in the carbonate region. Moreover, the ecological service data quantified in this study is for 2020 because we cannot determine whether the coordinates of *R. roxburghii* obtained indirectly (GBIF website and published papers) currently exist. We can be sure that 43 survey sites were planted with *R. roxburghii* before 2020, so these sites can be used to explore the relationship between *R. roxburghii* and ecological services.

The landscape in South China Karst is fragmented, and comparing ecological services of different land use types using raster data may affect the stability of the results. The farmland landscape was severely fragmented due to the extensive development of karst-soluble rocks and the uplifting effect of crustal movement. In this study, the spatial scale of ecological service data was 500 m because of the limitation of some underlying data resolution, for example, soil erosivity, evapotranspiration, and runoff. In fact, it was difficult to exceed this resolution for the area of *R. roxburghii* planting, and some other landscape types were inevitably mixed in the pixels. Ultimately, the impact of *R. roxburghii* monoculture on the deterioration of ecological services may be underestimated. In addition, the spatial

resolution of soil bulk density, coarse fragments, soil thickness, and bioclimatic variables was 1000 × 1000 m, which may also affect the accuracy of the results. Nevertheless, our study still presented a more reasonable result.

Conclusion

In this study, *R. roxburghii*, the ecological restoration species, was used to explore the pattern and driver of its suitability and its effect on ecological services. The study found that South China Karst is the most suitable area in the world for developing *R. roxburghii* industry, and the population distribution is the dominant variable controlling the distribution of *R. roxburghii* locally. The survey found that local farmers' pursuit of economic benefits drove them to form a monoculture model of *R. roxburghii*. Short-term *R. roxburghii* monoculture had higher economic benefits, but long-term monoculture led to the degradation of ecological services and reduced fruit yields. If monoculture continues, both the ecological environment and economic benefits will eventually be damaged. In the future, desertification control still needs to follow the path of agroforestry development and provide ecological compensation according to the ecological service supply capacity.

Abbreviations

NPP	Net primary productivity
SC	Soil conservation
WC	Water conservation
MSA	Mean species abundance
AGB	Aboveground biomass
SNI	Soil nutrient index
PSI	Provision service index
RSI	Regulation service index
SSI	Support service index
ESSC	Ecological service supply capacity
DEM	Digital elevation model
BD	Bulk density
CF	Coarse fragment
ST	Soil thickness
POP	Population
NDVI	Normalized difference vegetation index
LC	Land cover

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s40494-024-01521-w>.

Supplementary material 1. The Supplementary Material for this article can be found online at: Table S1 *Rosa roxburghii* geographic information of sampling localities. Table S2 Bioclimatic variables in Worldclim. Fig. S1 Schematic diagram of the selection of adjacent patches of non-*Rosa roxburghii*. Fig. S2 Schematic diagram of the selection of adjacent forest patch.

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Author contributions

XM, SZ, KX, and QY: conceptualization, methodology, writing-review and editing, validation, project administration and supervision; XM and SZ: software, formal analysis, data curation, writing-original draft preparation and visualization; XM, SZ and LW: validation, investigation and resources; QY: funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare no competing interests.

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