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A Study on the Spatial-Temporal Evolution of Greenhouse Areas in Mountainous and Plain Regions Based on Remote Sensing: A Case Study of Fujian Province

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Abstract:

With the development of facility agriculture, greenhouses have become an important part of modern agriculture, and timely mastery of the spatial and temporal trends of greenhouse area is of great significance for optimizing the allocation of agricultural resources and promoting sustainable development. Remote sensing technology provides an efficient means for greenhouse monitoring, which can realize the systematic analysis of changes in greenhouse area in topographically heterogeneous areas. In this study, the spatial and temporal changes of greenhouses in mountainous areas and plains in Fujian Province were analyzed based on Landsat remote sensing data from 2015 to 2024 using the random forest algorithm. The results show that spatially, greenhouses in the plains are concentrated and continuous, while greenhouses in the mountainous areas are distributed sporadically. In time, the area of greenhouses in the mountainous region increased dramatically at an average annual rate of 17.84%, from about 15 square kilometers to about 70 square kilometers. The plains, on the other hand, declined and then increased, with the total area showing a slow upward trend. The interaction of topographic, economic and policy factors together drove this spatial-temporal evolutionary process, and the results of this study can provide a scientific basis for the differentiated planning of agricultural greenhouses in Fujian Province.

Keywords: Remote sensing; agricultural greenhouses; Google Earth Engine; Landsat.

1. Introduction

With the continuous development of facility agriculture, greenhouse planting has become one of the key development methods of agriculture in many regions [1]. Agricultural greenhouses can accurately control temperature, humidity, light, and other environmental factors, providing good conditions for crop growth, and have strong advantages in improving the yield and quality of agricultural products. Rapid and accurate access to the area change of agricultural greenhouses is conducive to the adjustment of the agricultural development mode, to achieve the efficient use of agricultural resources [2].

The traditional agricultural greenhouse data acquisition mostly adopts sampling and statistical reporting methods, but due to the complex process, too much manual intervention and other issues, the accuracy and timeliness of the data are low [3]. In contrast, remote sensing, under the advantages of large-scale, multi-temporal observation, has gradually become the core means of monitoring spatial and temporal changes in agricultural greenhouses, thus facilitating the efficient use of agricultural resources.

Therefore, in recent years, medium-resolution remote sensing data based on remote sensing data processing and analysis platforms have been widely used for the identification and change analysis of greenhouses at global and regional scales. However, most of the existing studies focus on the distribution and change analysis of greenhouses in a single terrain area, such as Dou Yajuan's remote sensing monitoring of agricultural greenhouses in Beijing-Tianjin-Hebei region based on domestic satellite data [4], Zhu Dehai et al.'s study of spatial and temporal dynamics of agricultural greenhouses in Shandong Province in the past 30 years based on the GEE platform [4], and Gao Yuanyuan's study of agricultural greenhouses in Jilin Province based on multi-temporal remote sensing data [5], with the objects mostly being the North China Plain and the Northeast Plain, which are homogeneous terrain areas. Only a few scholars focus on other regions, such as Zixia Tang's study on remote sensing information extraction of agricultural greenhouses in Fujian Province [5], but the overall analysis of spatial and temporal differences of greenhouses in topographically heterogeneous regions and the multi-dimensional driving mechanism is still insufficient. Especially in Fujian Province, a typical region with many mountains and little land, there is a lack of targeted and systematic research.

At present, the distribution of agricultural greenhouses in China is mainly concentrated in Guangdong, Fujian, and other areas of South China with superior climatic conditions, while North China and Northwest China rely on advanced greenhouse technology and ecological restoration needs to form differentiated distribution characteristics [5]. Among them, Fujian Province has become a typical sample for the comparative study of greenhouse areas due to its diverse topography with both temperate climate and mountainous plains. Therefore, this study intends to focus on the topographic characteristics of Fujian Province, taking mountain greenhouses and plains greenhouses as research objects, using multi-temporal Landsat data to analyze the differences in the area distribution and expansion rate of greenhouses between the two types of regions in the past decade, and exploring the driving role of topography, economy, and policy on the spatial and temporal changes of greenhouses, to provide remote sensing data for the differentiated planning of facility-based agriculture in mountainous areas and plains.

2. Study area and data

2.1 Overview of the study area

In this study, Fujian Province was selected as the study area. Fujian Province is located in southeastern China, on the coast of the East China Sea, with a geographic location between latitude 23°33′-28°20′N and longitude 115°50′-120°40′E (Fig. 1), with a land area of 124,000 km2 and a sea area of 136,000 km2, which is an important outlet to the sea on the mainland of China. The terrain of Fujian Province is mainly mountainous and hilly, accounting for more than 80% of the total area of the province, with high relief in the northwest low relief in the southeast, and narrow plains along the coast. Climate belongs to the subtropical monsoon climate, an average annual temperature of 17 - 22 ℃, annual precipitation of 1400 - 2000 mm, and rain and heat at the same time, the ecological environment is superior, suitable for the growth of crops, is one of the country's main producing areas of vegetables and fruits [2] [6].

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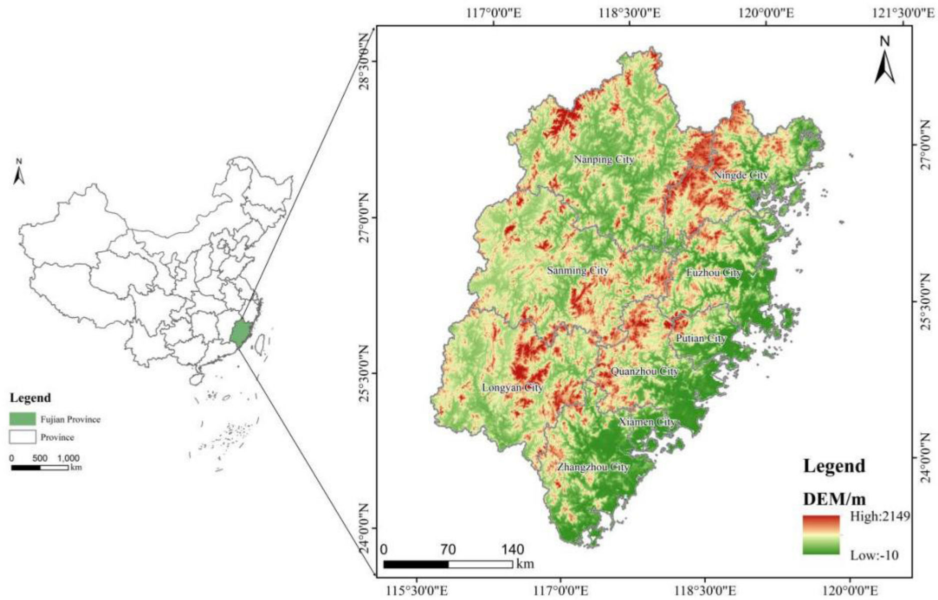

Fig. 1 Location map of the study area

2.2 Primary data sources

Landsat satellites are jointly implemented by the USGS and NASA, and have been continuously observing the earth from 1972 to the present, preserving a large amount of valuable historical image data. Landsat satellites image the earth's surface at 30m resolution with a re-entry period of about 14d, including multi-spectral and thermal data, which are widely used in land surveys, environmental monitoring, and other fields [3].

This paper intends to study the spatial and temporal changes in the area of mountainous and plain greenhouses in Fujian Province in the past ten years, so the year 2015 is used as the starting time of the study, and a total of four periods are selected to characterize the spatial and temporal changes in the past ten years, namely, 2015, 2019, 2021, and 2024, and the data of 2019 is selected due to the more cloudy and poorer quality of remote sensing imagery in Fujian Province in 2018. In this study, the cities of Zhangzhou, Fuzhou, Quanzhou, Putian, and Xiamen, which are distributed in the plain area of the southeast coast, are classified as plain study areas based on the topographic features and administrative divisions of Fujian Province; the rest of the cities, which are predominantly mountainous and hilly, including Nanping, Sanming, Longyan and Ningde, are categorized as mountain study areas.

3. Research Methods

3.1 Workflow

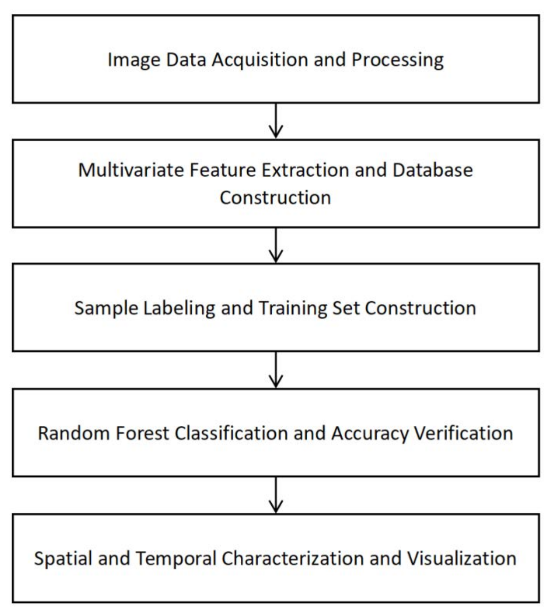

Fig. 2 Workflow diagram

This study is based on the Google Earth Engine (GEE) platform to carry out spatial-temporal analysis of the area of greenhouses in mountainous areas and plains of Fujian Province, the division of mountainous areas and plains is based on the degree of topographic relief and administrative divisions, aiming to reveal the similarities and differences in the distribution of greenhouses under different topographic conditions, and the flow of the study is shown in Figure 2. First, the Landsat 8-9 OLI image data of 2015, 2019, 2021, and 2024 were selected, and the image splicing, atmospheric correction, and de-clouded pre-processing were completed using the GEE platform function to guarantee the data quality. Secondly, a multi-source feature set is constructed from four dimensions: spectral, spectral index, texture, and topography, including B2-B7 band spectral data, six spectral indices such as NDVI and NDWI, 14 kinds of grayscale covariance matrix texture features, as well as four kinds of topographic features, namely, elevation, slope, slope direction, and mountain shadow, to form a 30-dimensional data-set. Then, 400 hut ROI were labeled based on the images in the mountainous and plain areas respectively, and 1600 non-hut samples were collected, which were divided into training and testing sets by 7:3 after the GEE spatial clustering to remove redundancy. Using the GEE machine learning module, a random forest model is constructed with 100 decision trees, input 30-dimensional features for training, and verified by the Kappa coefficient and other indicators to ensure that the classification accuracy is over 90%. Finally, the area of greenhouses in different years was counted, and the spatial and temporal distribution charts were produced to analyze the change characteristics and driving mechanisms.

3.2 Feature extraction

In order to fully integrate the respective advantages of radar and optical images and improve the extraction accuracy of agricultural sheds, this study constructs a multi-source feature space based on the extracted spectral bands B2-B7, also combined with spectral indices, texture features, etc., and all the feature calculations are realized in the gee platform [3,7].

3.2.1 Spectral features

Spectral features are the most basic features of the image, mainly reflecting the color and gray value features of each feature, and also the most important discriminating basis for distinguishing features [2], this study selected six key spectral features, as shown in Table 1.

Table 1 Spectral index formula

characteristic parameter	calculation formula
Enhanced Vegetation Index(EVI)[2]	EVI=2.5× ((NIR - Red) / (NIR + 6×Red - 7.5×Blue + 1)
Normalized Difference Water Index(NDWI)[2]	NDWI=(Green - NIR) / (Green+NIR)
Normalized Difference Vegetation Index(NDVI)[2]	NDVI=(NIR - Red) / (NIR+Red)
Land Surface Water Index(LSWI)[8]	LSWI=(NIR - SWIR1) / (NIR + SWIR1)
Normalized Difference Tillage Index(NDTI)[9]	NDTI=(NIR - Red) / (NIR + Red)
Green Normalized Difference Vegetation Index(GNDVI)[10]	NIR / Green - 1

3.2.2 Textural features

Although spectral information can reflect the inherent properties of features, in the extraction of agricultural greenhouses, the high reflection and transmission of visible light from greenhouse materials, superimposed on the changes in lighting conditions and atmospheric interference can lead to the phenomena of the “same spectrum, different objects” and “the same object, different spectrum”, which can lead to confusion in the classification results. The phenomenon of “same spectrum” and “same substance different spectrum” will lead to the confusion of classification results. Agricultural greenhouses are mostly rectangular and arch-shaped with obvious geometric texture features, so texture features are introduced in this study to improve the classification accuracy [7]. Gray-Level Co-occurrence Matrix Texture (GLCM), a function for fast calculation of GLCM - Based texture features, is provided by GEE, with a total of 14 texture features:Angular second-order moments (ASM), contrast (CONTRAST), correlation (CORR), variance (VAR), inverse variance moments (IDM), sum-mean (SAVG), sum-variance (SVAR), sum-entropy (SENT), entropy (ENT), difference-variance (DVAR), difference-entropy (DENT), correlation-information measure (IMCORR), disparity (DISS) and moment of inertia (INERTIA) [2].

3.3 Category

After feature extraction is completed, the multi-source features are integrated into a unified dateset, which is used as an input variable for the training of the agricultural greenhouse classification model. The land use types are divided into two categories: agricultural greenhouses and other features: among them, agricultural greenhouses cover facilities such as continuous greenhouses, solar greenhouses, plastic greenhouses and small arched greenhous-

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es; and other features include irrigated and non-irrigated farmland, lakes, rivers, settlements, factories, and other land types.

This study adopts the sample collection method combining manual interpretation and stratified sampling. Based on Google Earth high-resolution images, 400 agricultural greenhouse ROI were manually labeled in the mountainous and plain areas of Fujian Province, respectively, and 1,200 non-greenhouse feature samples (including three typical land types: forests, water bodies, and construction land) were collected simultaneously. Finally, a dataset containing one greenhouse sample and one non-greenhouse sample was formed and randomly divided into training set and validation set with 7:3 ratio.

3.4 Random forest algorithm

In this study, a random forest algorithm is used to construct an agricultural shed classification model based on the GEE platform. Random forests can deal with high-dimensional covariance features and have been widely used in the field of remote sensing image classification, so it is suitable for the task of remote sensing classification of greenhouses in this study [3].

The key parameters of the random forest classifier are n tree (the number of decision trees) and the m try (the number of features randomly extracted during the training of a single tree). Optimized by cross-validation experiments, n tree = 100 is set in this study to ensure model convergence; m trying is the square root of the total number of features, which balances model complexity and classification accuracy. During the training process, the model constructs a single decision tree by self-sampling 2/3 training samples with a random subset of features, and the final output is generated by voting on all the decision trees to realize the batch classification of Landsat images in the study area.

In addition, in order to evaluate the quality of the classification results, two methods, confusion matrix, and visual assessment, are used in this study. Visual assessment is used to directly analyze the classification results, which is the most direct and basic method. The confusion matrix comes from the test samples and calculates the overall classification accuracy, Kappa coefficient and other indicators [3].

4. Results and analysis

4.1 Analysis of temporal and spatial changes

4.1.1 Differences in the spatial distribution of mountain and plains greenhouses

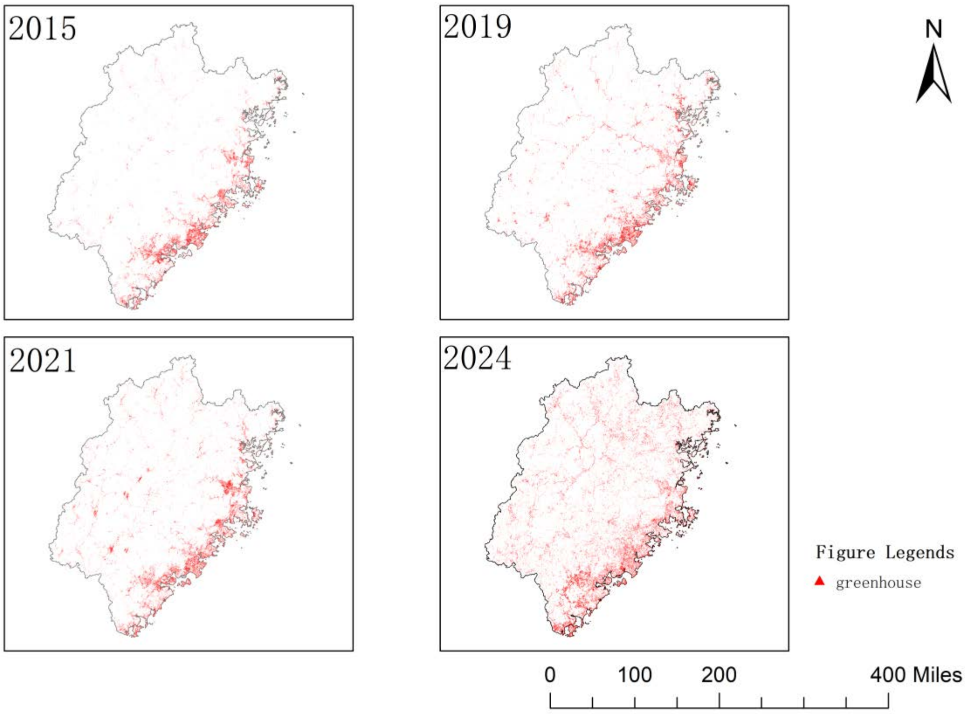

Fig. 3 Distribution of greenhouses in Fujian Province

The study shows through validation that the overall accuracy of the classification model is more than 90%, and the Kappa coefficient is stable above 0.98, so the results have good reliability and accuracy. Based on this reliable result, the distribution map of greenhouses in Fujian Province from 2015 to 2024 was derived as shown in Fig. 3. In terms of spatial distribution, the area and distribution of greenhouses in the mountainous areas and plains of Fujian Province show significant regional differences: greenhouses in the plains are concentrated in the southeast coast and have been distributed continuously since 2015 to form a large-scale industrial cluster, but in the past ten years, as can be seen in Fig. 3, there has been a tendency to spread to the north and the south to a certain extent; mountainous greenhouses are scattered in the mountain basins and valleys in the central and northern parts of the study area, and although the number and extent of them have increased by 2024, the overall number and extent are still high, and the number of greenhouses in Fujian Province has increased. Although the number and scope of these huts will increase by 2024, they are still scattered, and the degree of clustering is significantly lower than that in the plains.

4.1.2 Differences in temporal variation between mountain and plains greenhouses

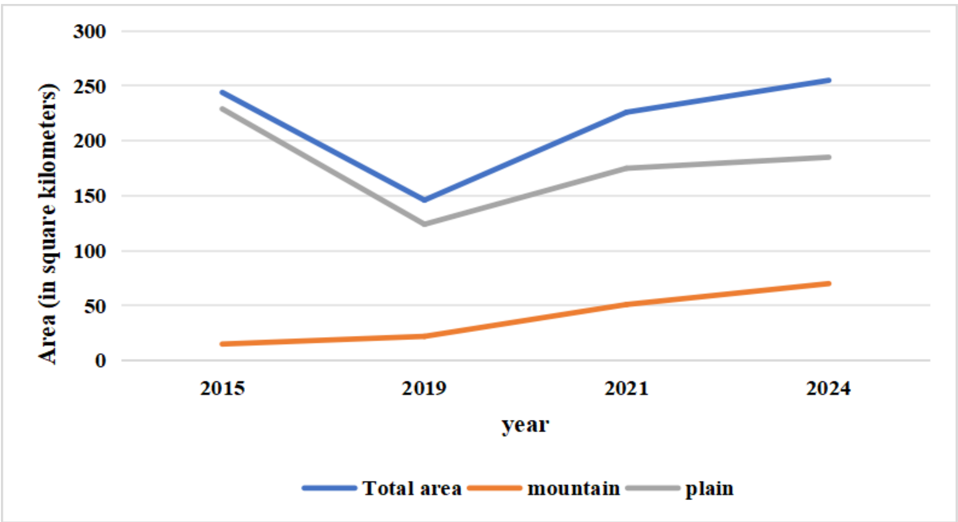

Fig. 4 Line graph of changes in the area of greenhouses in Fujian Province in the past ten years

Fig. 4 visualizes the changes in the total area of greenhouses in Fujian Province, and the areas of greenhouses in mountainous areas and plains in the time series in the form of a folding line. 2015 - 2019, the area of greenhouses in mountainous areas gradually expanded at an average annual rate of about 10.1%, from about 15 square kilometers in 2015 to about 22 square kilometers in 2019; while the area of greenhouses in plains shrunk significantly at an average annual rate of about 16.6%, from about 229 square kilometers in 2015 to about 124 square kilometers in 2019. from about 229 square kilometers in 2015 to about 124 square kilometers in 2019.In 2019 - 2021, the development trend of the two shifted, and the area of the mountain area of greenhouses entered a period of rapid growth, with an average annual growth rate of about 69.8%, far exceeding the average annual growth rate of about 20.2% in the plains, and the development momentum was strong. In 2021 - 2024, although the area of the mountain area and plain area of greenhouses still maintains the growth In 2021 - 2024, although the area of greenhouses in mountainous areas and plains still maintains the trend of growth, the growth rate slows down significantly, with the average annual growth rate in mountainous areas dropping to about 10.4%, and about 1.9% in plains, and the growth tends to be stable. Overall, in the past ten years, the total area of greenhouses in Fujian Province has been a slow upward trend, in which the area of greenhouses in mountainous areas has increased significantly at an average annual rate of 17.84%, from about 15 square kilometers in 2015 to about 70 square kilometers in 2024, and the area of greenhouses in the plains has declined and then risen, and the overall change has not been significant.

In terms of the proportion situation, the proportion of mountainous areas of greenhouses to the total area continues to climb, steadily increasing from 6.2% in 2015 to 27.5% in 2024, with an increasingly important position in the greenhouse industry. The change in the proportion of the area of greenhouses in the plains is more tortuous, with a sharp decline in the first period, from 93.8% to 84.9% between 2015 - 2019; and a gradual rebound in the later period, to 72.5% between 2019 - 2024, showing a contraction followed by a recovery, reflecting that the

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greenhouse industry in the plains seeks a new path of development in the midst of dynamic adjustments.

5. Driver analysis

From the above analysis of the spatial and temporal changes in the area of greenhouses in Fujian Province from 2015 to 2024, it can be seen that the distribution of greenhouses in Fujian Province shows a trend of gradual increase in the mountainous areas from scattered and a centralized and continuous and fluctuating scale in the plains. The difference between the distribution of greenhouses in mountainous areas and plains is significant and evolving, and an in-depth analysis of the driving factors of such spatial and temporal differences will help to understand the development law of facility agriculture in different topographic regions and provide a scientific basis for regional agricultural planning. Therefore, this study mainly analyzes the driving factors from three dimensions: terrain, economy and policy:

5.1 Topographic factor

Topography greatly restricts the scale and distribution of greenhouse construction. Plain terrain is flat and open, conducive to large-scale agricultural operations and large-scale layout, can effectively reduce the unit construction and management costs, and is the ideal area for the centralized development of greenhouses. The mountainous terrain is complex, mountainous hills are widely spread, the plot is broken and the slope is large, not only the construction difficulty and cost increase dramatically, but it is also difficult to plant on a large scale, and it can only be distributed sporadically in mountain basins, river valleys and other localized gentle places. From the chart, from 2015 to 2019, the area of greenhouses in the plains declined because the available land was occupied by urban construction, etc. Although the mountainous areas grew slowly, there was still a certain growth due to the availability of localized gently sloping land and the difficulty of expanding due to the restrictions of the terrain. 2019 - 2021, the growth rate of the mountainous areas accelerated thanks to the further excavation of localized suitable space for construction; the growth rate of the plains was slow due to the limited area suitable for large-scale construction. From 2021 to 2024, the growth rate of mountainous areas will slow down, highlighting the rigid constraint of scarce land resources; the area of plains will rebound but with a small amplitude, and it will be difficult to expand on a large scale due to terrain constraints.

5.2 Economic factor

The level of economic development and market demand have a profound impact on the change of greenhouse area. 2015-2019, economic growth and urbanization promote the upgrading of agricultural consumption, and the demand for anti-seasonal and high-quality fruits and vegetables increases greatly. The plains attract capital and form industrial clusters by transportation and market advantages; mountainous areas grow faster than the plains due to low land and labor costs and strong demand for specialty agricultural products. 2019, the economic environment fluctuates and market saturation leads to a decline in the rate of return on investment, and the expansion of greenhouses on the plains is the first to slow down. 2021-2024, the economic growth rate slows down, competition intensifies, and the mountainous areas are weak in resistance to risk, so they are still growing, but the rate of growth is much lower than that of the plains. Plains. In the chart, in 2019 - 2021, the slope of mountainous areas is large, and the plains are flat; in 2021 - 2024, the slope of mountainous areas becomes smaller, and the plains do not change much, which all reflect the influence of economic factors.

5.3 Policy factor

Policy orientation plays a key role in promoting and regulating the development of greenhouses. In 2015 - 2019, Fujian Province introduced some policies to support facility agriculture, such as subsidizing the construction of agricultural greenhouses and promoting advanced planting technologies, which stimulated the enthusiasm for greenhouse construction in mountainous areas and plains [11]. However, the plains are affected by the strengthening of the implementation of land use-related policies, and some land has been expropriated due to urban construction, industrial development and other needs, leading to a reduction in the land used for greenhouse cultivation and a decline in the area of greenhouses [12]. At the same time, the ecological environmental protection policy is tightening, such as on the plains of agricultural surface pollution management requirements to improve, part of the greenhouse does not meet the environmental requirements of the greenhouse was rectified or demolished, but also makes the plains greenhouse area shrinking. And mountainous areas due to the development of relatively decentralized, affected by the policy is small, and through the guidance of the development of ecological agricultural greenhouses to promote the branding of special agricultural products, greenhouse areas still maintain a certain growth. 2019, the ecological protection policy is further tightened, mountainous areas, part of the greenhouses in ecologically sensitive areas in violation of the construction of the greenhouse was demolished, the rate of expansion is limited [13]. The layout of greenhouses in the plains is relatively regular, and the degree of influence is relatively small. 2021 onwards, the policy focus turns to the green transformation of agriculture and quality and efficiency, the plains, by virtue of the capital and technical advantages, upgrading the facilities of greenhouses, optimizing the planting structure, and the area share rebounded; mountainous areas are subject to the limitations of resources and technology, and the rate of growth is slower. From the chart, it can be seen that in 2019 - 2021, the growth rate of mountainous areas is fast, which is related to the policy support for ecological agriculture in the previous period; in 2021 - 2024, the plains will rise, and the mountainous areas will flatten out, which is in line with the change of policy orientation.

6. Conclusion

Based on the multi-temporal Landsat remote sensing data, this study systematically analyzes the spatial and temporal differences in the area of greenhouses between the mountainous areas and the plains of Fujian Province in the past decade and their driving mechanisms by relying on the platform of GEE and the Random Forest Algorithm. The study confirms that the remote sensing technology has high efficiency and accuracy in monitoring greenhouses at the regional scale, and the overall accuracy of the classification model exceeds 90%, with the Kappa coefficient stabilized above 0.98. Spatially, the distribution of greenhouses in Fujian Province is characterized by significant topographic differentiation, with greenhouses in the plains concentrated in the southeast coast forming large-scale industrial clusters, while greenhouses in the mountainous areas are scattered in the river valleys and basins in the central and northern parts of the province, and are relatively small in scale. On the time series, the total area of greenhouses in Fujian Province in the past ten years showed a slow upward trend, in which the area of greenhouses in mountainous areas increased significantly at an average annual rate of 17.84%, from about 15 square kilometers in 2015 to about 70 square kilometers in 2024, while the area of greenhouses in the plains declined first and then rose, with little overall change. This trend is mainly influenced by the combination of factors such as topographic conditions, level of economic development and policy support.

However, despite the achievements, this study has some errors, which may be due to the fact that only 30m resolution Landsat images are used as the data source, which makes it difficult to recognize the small or complex structures of greenhouses; the classification model is affected by the phenomenon of "homo-spectral heterogeneity", and the manual interpretation of the samples may also generate subjective errors, and so on. In the future, we can consider integrating high-resolution remote sensing, radar and other multi-source data to improve the recognition accuracy, introduce deep learning algorithms to optimize the model, and also consider using geographic probes and other methods to quantify the driving mechanism, so as to explore the spatial and temporal pattern of change of greenhouses in a more in-depth manner, and promote the sustainable development of regional agriculture.

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