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Rural economic benefits of land consolidation in mountainous and hilly areas of southeast China: Implications for rural development

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ABSTRACT

Land consolidation has become a massive organized activity and is widely implemented in rural areas. However, research remains somewhat scarce on the contributing mechanism of land consolidation with production factors to regional rural economies. In this study, we sampled 4710 land consolidation projects during the year of 2006–2016 and recorded their benefits to the rural economies within the project area, in the mountainous and hilly rural areas in Southeast China. A random forest (RF) model was used to explain the variation of rural economic indicators quantitatively and partition the relative importance of each factor from land consolidation projects. The results showed that land consolidation contributed to the promotion of rural economies. The R^2 of the RF models were 66.55% (for grain production increment), 55.19% (for net agricultural income increment), 37.01% (for land rental income), and 42.60% (for labor income) respectively. Despite the direct input factors especially newly added cropland area and total investment of land consolidation project dominant across the study area, the most important factors varied over the years and across counties considerably. Noteworthily in specific years and several counties (e.g. those in the north of study area), factors reflecting technological efficiency such as the mechanized agricultural area and the land-leveling area could also make primary contribution to grain production increment and net agricultural income increment. Moreover, the marginal returns law and the scarcity of land resources in the mountainous and hilly areas were also suggested. The results revealed the significance of engineering measures for technological efficiency. The study highlights the importance of land consolidation to regional rural economies in mountainous and hilly areas, and provides valuable insights for promoting the efficiency of regional rural land consolidation arrangements in the future.

1. Introduction

Regional rural economic development is important in modern society, and has for many years attracted the attention of researchers interested in revealing its influential factors, including micro-to macro-economic components such as capital (Meslier-Crouzille et al., 2012), labor (Qian et al., 2016; Qin and Liao, 2016), technology (Davis et al., 2012; Khan et al., 2014), industry (Slee et al., 2004; Zhang et al., 2016), ownership and policy (Van der Ploeg and Renting, 2000; Lawley and Furtan, 2008; Headey et al., 2010; Phimister and Roberts, 2012). Initially proposed to address fragmentation problems, land consolidation is an approach to the comprehensive treatment of unused, inefficient, and idle land, and land that is damaged or degraded. As such, land consolidation has been implemented worldwide in rural areas, with many concerned about its impact on rural development (Pašakarnis and Maliene, 2010; Long et al., 2012; Yan et al., 2015; Moravcová et al., 2017; Zeng et al., 2018).

Agricultural land consolidation is the main type of land consolidation, altering the patterns of cropland, irrigation, roads, and villages for the sake of promoting rural development. On the one hand, policy and institutional frameworks in land consolidation are generally the basis for adjusting and exchanging land ownership, so as to reduce land

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scattering and fragmentation and improve agricultural productivity (Korthals Altes and Im, 2011). For example, Pašakarnis and Maliene (2010) suggested that in Central and Eastern Europe, the consolidation policy of land ownership was an effective management instrument that could readjust unfavorable fragmentation and promote the combination of land, and that it could deliver sustainable rural development. Moreover, Lisec et al. (2014) showed that both institutional (legal) frameworks and informal institutions such as traditions, emotional bonds to land, culture, and habits were important for developing good land consolidation practices in Slovenia. Haldrup (2015) revealed that agreement-based land consolidation modes in Denmark, which insisted on the active participation of individual landowners, could promote mutual trust among stakeholders and coordinate social development. Li et al. (2018) noted that policy that encouraged the transfer of land operation rights and expanded the rural land market was crucial for scaled land operations and for reversing so-called village hollowing in China.

On the other hand, in designing projects, land consolidation includes a series of engineering measures to stimulate economic and social development. Leveling land for mechanized cultivation of soil is a primary aim of land consolidation to improve spatial and economic conditions for farming (Kupidura et al., 2014), and Li et al. (2014) discussed a case where reclaiming scattered rural residential land could improve agricultural production in China. Additionally, improving the quality of rural roads and transportation networks is one of the most significant measures for economic efficiency (Papoušek, 2011), especially in mountainous areas (Janus et al., 2017). Constructing irrigation and drainage and integrating water management are also considered means of supporting farming and other functions (Van den Brink and Molema, 2008; Stańczuk-Gałwiaczek et al., 2018). Among this research, however, quantitative analysis with multiple measures and the mechanism of promotion remains scarce, mainly due to the general unavailability of detailed information regarding land consolidation and its socio-economic benefits.

Indeed, many studies cover only a limited number land consolidation projects or rural areas with projects to reveal the rural economic benefits. It is commonly suggested that land consolidation has positive impacts, according to statistical changes pre- and post-project, in terms of specific socio-economic indicators (Sklenicka, 2006; Fan et al., 2016; Muchová et al., 2017), and stakeholder satisfaction that may be prone to error owing to their subjectivity (Yaslioglu et al., 2009; Cay and Uyan, 2013; Lisec et al., 2014; Luo and Timothy, 2017). It is worth mentioning that Wu et al. (2005) selected only two counties in China and used information from 227 rural families to indicate statistically positive effect of land consolidation projects on the grain output of these families.

Regretfully, there is little research available with an appropriate sample size for land consolidation projects. Although the aforementioned studies demonstrated rural economic benefits based on limited-number projects, there is little quantitative information regarding the importance and contribution of the various factors that pertain to land consolidation, such as the direct input factors including the newly added cropland area and the total project investment, and engineering technologies for agricultural land-leveling, field roads, irrigation and drainage, shelter-forest, and so forth. Moreover, several studies recently suggested that distinguishing these factors could be essential for target-poverty alleviation and rural development in China (Li and Yang, 2018; Liu et al., 2018; Long et al., 2018). Thus, the mechanism by which land consolidation benefits the regional rural economies requires revealing.

In China, land consolidation was initially implemented for food security in 1998 and proposed as a national policy to promote rural economic and social development in 2008. Nowadays, land consolidation is a massive organized human activity (Wang and Zhong, 2016), with at least 17,000 projects and a total area of around 1.5 million ha occupied every year averagely (2006–2016), according to the China Land and Resources Almanac. Fujian Province in Southeast China is the main area in the Western Taiwan Straits Economic Zone, a national strategy. Much attention has been given to the rural economy and society in this region (Zhang and Cai, 2008; Zhong et al., 2011; Chen et al., 2017). Unlike the plains in northern China, however, Fujian has many mountains and hills with basin valleys, resulting in somewhat limited potential for agricultural improvement. Thus, a viable plan and design for land consolidation is especially important there. Over the last decades, more than 10,000 land consolidation projects have been implemented in Fujian, but their effectiveness has received little attention, especially with regard to the rural economic benefits of land consolidation in this region.

In this study, we collected information from 4710 land consolidation projects in the year of 2006–2016, covering the entire distribution range of projects in Fujian Province. Considering a project area as a statistical unit, detailed information regarding rural economic improvement pre- and post-project was recorded, including the increment of grain production and net agricultural income, and the local farmers' incomes from land rent and labor in project construction. Then, using random forest (RF) model, we attempted to answer the following three questions: (1) How does land consolidation and its important factors promote regional rural economies? (2) How do these important factors vary over the years in the study area? And (3) how do the important factors differ spatially in study area? The results of this study could provide valuable insights for understanding the contributing mechanism of land consolidation with its multiple features to rural economic benefits, and for promoting the efficiency of regional rural land consolidation arrangements in mountainous and hilly areas.

2. Data and methods

2.1. Study area and project samplings

With 85 counties and a total area of 1.24×10^5 km^2, Fujian Province is located in Southeast China (ca. 23°33′–28°20′N and 115°51′–120°51′E) (Fig. 1a), adjacent to Taiwan Island with the separation of the Taiwan Strait. Vast rural areas inland and narrow coastal areas with relatively developed regions shaped the socio-economic patterns in the province (Bai et al., 2009; Ke and Lu, 2011; Wang and Wang, 2011). Notably, land consolidation arose in these mountainous and hilly areas recently to improve local agricultural conditions. In 2016, the value of the agricultural gross domestic product per capita in Fujian was 38,390 Yuan, higher than the national value (29,620) and that of the Western Taiwan Straits Economic Zone (28,200), according to the Statistical Yearbook of China.

To evaluate the rural economic benefits of land consolidation, with the Land Development and Consolidation Center of Fujian Province, we sampled annual projects and recorded the corresponding information from 2006, with a sampling proportion of around a third in each county in a year. A total of 4710 land consolidation projects were sampled among the thousands during 2006–2016, covering most counties (73 of 85 counties) in Fujian, with the exception of coastal regions with relatively scarce rural areas (Fig. 1a and b). These projects were all implemented in winter to avoid delaying annual farming activities before and after the project, as local farming takes place from spring to autumn. Meanwhile, there was little change in the farming structure in the two successive years pre- and post-project, and, according to the national policies, repeated projects are prohibited in the same area. Thus, we could observe the direct effects of land consolidation, such as its

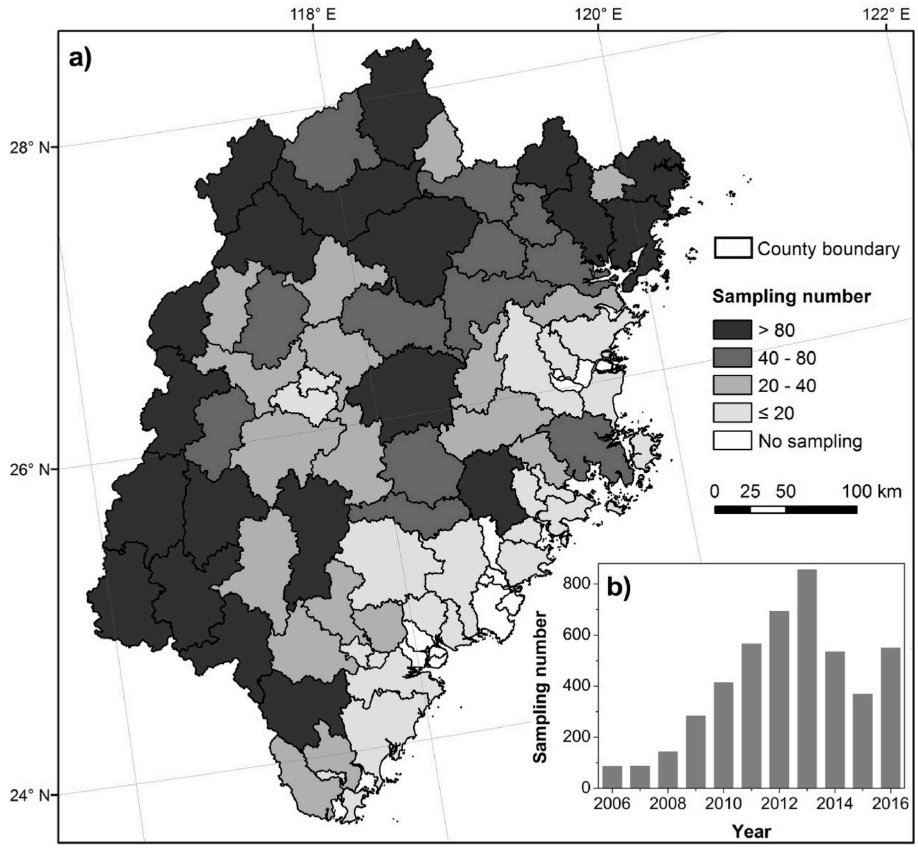

Fig. 1. The location of Fujian Province with sample distribution among counties in a) and years in b).

contribution to the changes in grain production and other income over the two-year period.

2.2. Description of data

With the help of the Land Development and Consolidation Center of Fujian Province, we recorded four indicators of economic benefits in each project area over two successive years pre- and post-land consolidation (Table 1). First, the grain production increment (GPI) indicates the difference between the values of two-year actual yields. In each year, for the sampled projects, we worked with local agricultural technology stations and the land & resources office as well as with the farmers involved to measure the grain production before the project started in winter. In order to ensure the value of grain production relatively accurate, we selected several representative parcels whose grades[1] were the most closest to the average grade across the project area, to measure the yield per area and then calculate the actual yield. Likewise, we measured the output at harvest the following year. The mean GPI among the 4710 projects was 0.56 (± 2.13) × 10^5 kg (after eliminating outliers, similarly hereinafter). Second, to calculate of net agricultural income increment (NAII) between the two successive years, joint works with the township finance office, statistics station, and village committee were conducted. We randomly selected more than 10% of rural families within the project area, and each household's net agricultural income and family size were recorded at the end of each year. Then, the sum of net agricultural income and the sum of the size

Table 1
The 4 response indicators and 14 contributing factors within sampled projects.

Variables (Abbreviation), (Unit)	Average	Standard deviation
Grain production increment (GPI), (kg)	0.56 × 10^5	2.13 × 10^5
Net agricultural income increment (NAII), (Yuan)	1.14 × 10^6	7.92 × 10^6
Land rental income (LRI), (Yuan)	1.32 × 10^5	3.71 × 10^5
Labor income (LI), (Yuan)	0.85 × 10^5	2.01 × 10^5
Total area (TA), (ha)	31.19	57.79
Total investment (TI), (10 thousand Yuan)	59.41	161.19
Total number of people (TNP),	558.88	1534.15
Newly-added cropland area (NACA), (ha)	5.66	9.61
Mechanized agricultural area (MAA), (ha)	20.72	43.53
Land-leveling area (LLA), (ha)	16.39	42.39
Farm road length (FRL), (km)	2.98	6.94
Irrigation and drainage length (IDL), (km)	3.67	8.19
Other water conservancy facility number (OWCFN),	9.48	52.62
Electric transmission line length (ETLL), (km)	0.01	0.15
Shelter-forest tree number (SFTN),	26.49	537.16
Erosion-control area (ECA), (ha)	3.59	21.13
Agricultural enterprise number (AEN),	0.21	1.61
Agricultural enterprise area (AEA), (ha)	3.42	18.94

Notes: the data of LRI and LI were based on 391 projects with land transfer and land rent and 1486 projects with labor involved in project construction, respectively. Contributing factors were all from recording of the project construction. TNP: the total number of people living within the project area. LLA: the total area of fields where measures were taken to make the land flat. FRL: the total length of field roads and production roads. OWCFN: the total number of agricultural bridges, culverts, wells, ponds, sluices and pumps. ETLL: the total length of transmission lines for high- and low-voltage power for using water conservancy facilities. AEA: the total area occupied by agricultural enterprises originating with land transfer.

[1] The grade of agricultural land in China is defined according to the National Standard 'Regulation for gradation on agriculture land quality', which has considered the natural and technological conditions of agricultural land with adjustment based on related historical records.

of all selected families could be calculated, and their ratio was multiplied by the total number of people living within the project area, resulting in the net agricultural income value of each year. Thus, NAII could be derived. The mean NAII among the 4710 sampled projects was 1.14 (± 7.92) × 10^6 Yuan. Finally, the remaining two indicators—the local farmers' land rental income (LRI) and labor income (LI) from project construction—were respectively recorded from farmers involved in land transfer and project construction from land consolidation, with the help and confirmation of township institutions and construction companies for the project. There were 391 projects with farmers involved in land transfer, and 1486 projects with farmers involved in project construction. The mean LRI for those projects was 1.32 (± 3.71) × 10^5 Yuan, and the mean LI was 0.85 (± 2.01) × 10^5 Yuan. These data collections were conducted in the field, with timely recording and multi-institutional participation from stakeholders, ensuring the relative accuracy of the assessment data for these 4710 projects selected from a total of over 10,000.

As potential contributing factors, the characteristics recorded for land consolidation projects were applied to the following quantitative analyses. Information for factors reflecting the direct inputs to agricultural production were recorded when the project was implemented: namely, the total area (TA) within the project, the total investment (TI) of the project, the total number of people (TNP) living within the project area (only used in the mechanism analyses for GPI), and the newly added cropland area (NACA) as a result of the project. Moreover, according to the national policy, there are four general engineering measures in land consolidation projects in China for improving the quality of cropland and the productivity in rural areas (Wang et al., 2018). The corresponding factors for technological efficiency from engineering were applied.

The first measure is land-leveling, including flattening and connecting adjacent fields, filling land from abandoned ditches and pits, and so forth, to increase the effective cropland area. Though land-leveling, the physical and chemical properties of soil can be improved, facilitating cultivation and even mechanized agriculture (Khan et al., 2007; Öztekin, 2013). Consequently, two factors were recorded, the mechanized agricultural area (MAA), and the land-leveling area (LLA) of the fields where the measure was adopted. The second measure is the construction of farm roads, which proves to be essential to promoting agricultural production (Janus et al., 2017; Löw et al., 2017). The farm road length (FRL) was used, which includes the total length of field roads and production roads. The third measure is agricultural hydraulic engineering, whose role in facilitating agricultural production has long been recognized (Smedema et al., 2000; Makombe et al., 2007; Shao et al., 2015). Three factors relating to hydraulic engineering were recorded and applied in this study: the agricultural irrigation and drainage length (IDL); the water conservancy facility number (OWCFN), which includes the total number of agricultural bridges, culverts, wells, ponds, sluices, and pumps; and the electric transmission line length (ETLL), which includes the total length of transmission lines for high- and low-voltage power for using water conservancy facilities. The fourth measure is erosion control, to provide shelter belts for cropland (Golosov and Belyaev, 2013; Amichev et al., 2016). The shelter-forest tree number (SFTN) and erosion-control area (ECA) were thus considered. Finally, as Lerman and Cimpoieş (2006) suggested that agricultural enterprises originating from land consolidation could promote rural development in Central Europe, agricultural enterprises were also taken into account in this study. Thus, the agricultural enterprise number (AEN) and area (AEA) occupied by these enterprises were considered as contributing factors for following analyses. The basic statistical information for all aforementioned factors within the samples is given in Table 1.

2.3. Statistical analyses

Although production function models have long been popularly applied in research on land output and its economic benefits (Cornia, 1985; Walpole et al., 1996; Omonona and Sopitan, 2006; Tran et al., 2016), it is difficult to partition specific technological components and their respective contribution. In this study, however, we had derived several factors reflecting technological efficiency from land consolidation project information, as well as the direct inputs to production, as mentioned above. At regional scale, the mechanisms of land output and other rural economic benefits from each factor, and also the relationships of these multiple factors, are not clear. In this instance, we used RF model for an exploratory purpose, to analyze the promotion of land consolidation projects and the contribution of each factor to rural economic benefits, as the RF model is a machine learning method with ability to handle interactions and nonlinearity among variables (Breiman, 2001). For a long time, the RF model has been widely applied to analyze the complex mechanisms in earth-surface processes in natural and social coupling systems (Francke et al., 2008; Oliveira et al., 2012; Wang et al., 2015; Lopatin et al., 2016; Brokamp et al., 2018; Ying et al., 2018). And it has recently been introduced to economic and industrial systems to deal with perplexing human activities (Everingham et al., 2016; Weinblat, 2018). Therefore, it must be reasonable for using the RF model to explore the mechanisms and evaluate the rural economic benefits of land consolidation.

For the 14 contributing factors (explanatory variables) in Table 1, the RF model was used to account for the variations in GPI, NAII, LRI, and LI (response variables) across the study area, in each year from 2006 to 2016 and in each of the 73 counties studied. Generally and practically, we used the value of the natural logarithm (ln-) of each response variable. The best RF model was detected with the criterion of the minimum mean square error (MSE) from out-of-bag (OOB) data (Breiman, 2001). In this method, there were 500 trees to grow in the RF model of each factor combination, while the tree is known as regression tree[2] for continuous variable. For each tree, random samplings with replacement were applied to generate the training set until the size of set equaling the number of samples in the model. Thus around a third of the samples, the so-called OOB data, were not used as training data of each tree. Then, the squared residual of each OOB sample was detected among the trees without containing the sample as the training case, but rather as the testing case. Thus, the mean squared residual among samples could be calculated as the MSE of the OOB data of the model. In the final best RF model, the relative importance of each factor could be represented by the increase in MSE (IncMSE) of the OOB data when the value of the factor was permuted randomly (Liaw and Wiener, 2002; Breiman, 2003). The most important factor with the largest IncMSE was considered the primary factor. Finally, partial dependence plots (PDPs) were used to reflect the marginal response of rural economic development to each contributing factor (Breiman, 2001; Friedman, 2001). For each contributing factor, the *x*-axis of PDPs was within the value range of the factor, and for a specific *x*-axis value, the corresponding *y*-axis value of PDPs (i.e. the value of economic indicators) could be calculated by the best RF model. Practically, the contributing factor fixed with the specific *x*-axis value, the predictive was averaged as the related *y*-axis value with all combinations of other explanatory variables in the model. These statistical analyses were performed in R v3.4.1, and spatial displays used ArcGIS v10.3 with the Asia Lambert Conformal Conic projection.

[2] For prediction, regression tree is one kind of decision trees for continuous variables, while for discrete variables classification tree will be used.

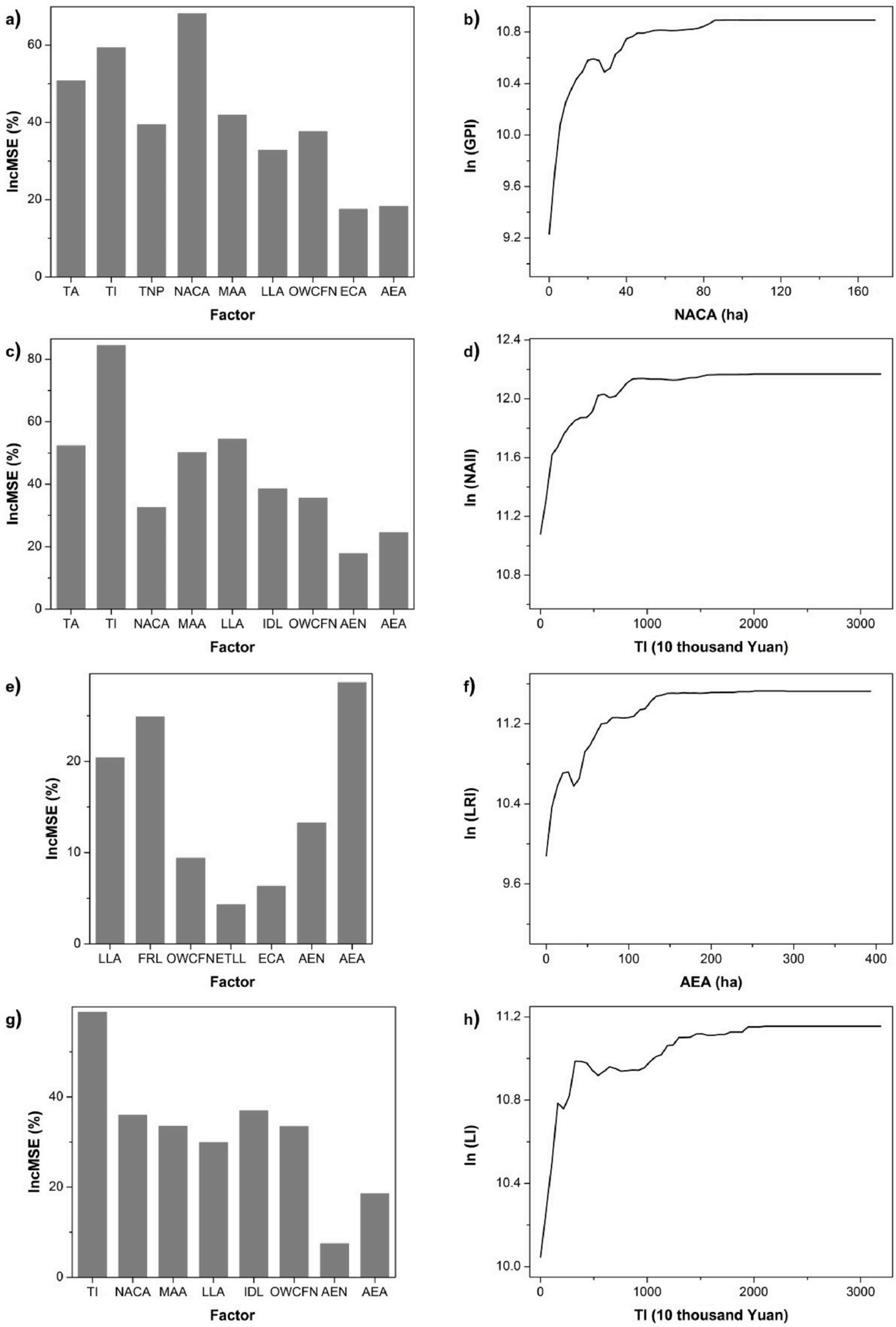

Fig. 2. The importance of each factor represented by the increase of mean square errors (IncMSE) of OOB data in the best random forest models for a) (ln-) GPI, c) (ln-) NAII, e) (ln-) LRI, and g) (ln-) LI, while the corresponding marginal response to the most important factor showed with the partial dependence plots in b), d), f), and h) respectively.

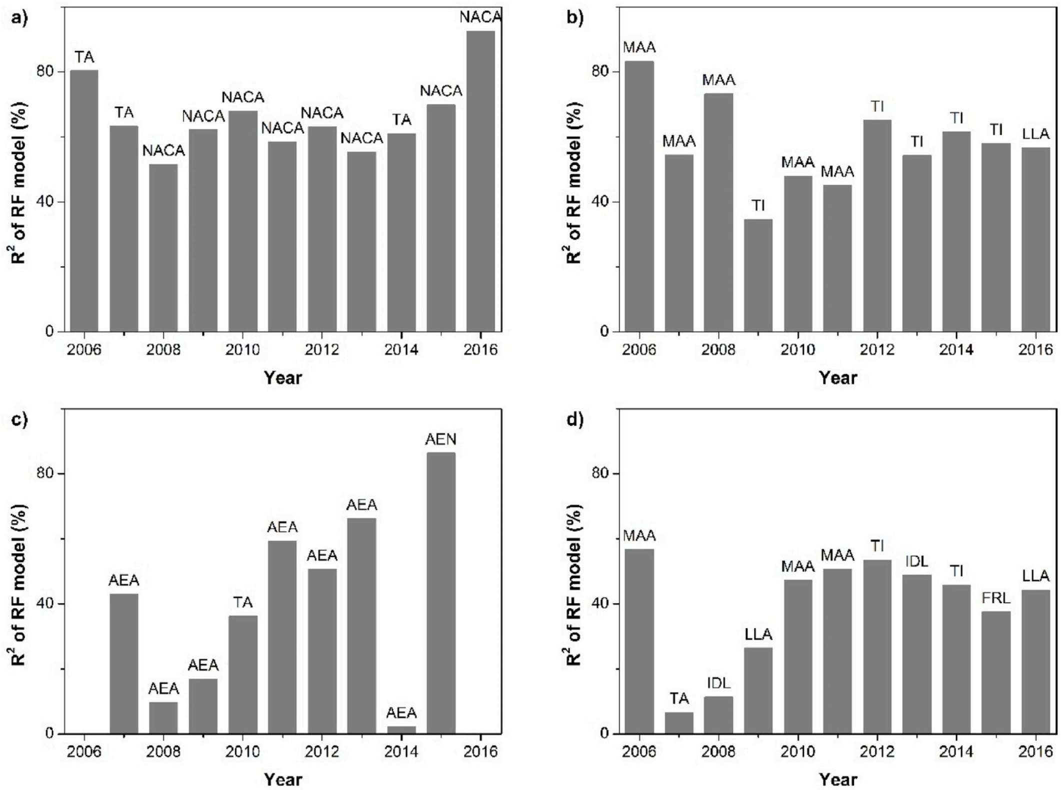

Fig. 3. R^2 of the best random forest (RF) model over years for a) (ln-) GPI, b) (ln-) NAII, c) (ln-) LRI, and d) (ln-) LI, noting that no suitable RF model for (ln-) LRI in 2006 and 2016, while the primary contributing factors in the corresponding model were shown above the column.

3. Results

3.1. Contributing factors to the regional rural economies from land consolidation

Across the 4710 land consolidation projects, the final RF model accounted for 66.55% and 55.19% of the variation in (ln-) GPI and NAII, respectively. In each RF model, there were nine contributing factors, of which the most important were the direct production input, newly added cropland area (NACA), and total investment (TI) (Fig. 2a and c). Meanwhile, the (ln-) GPI and NAII both revealed stepwise marginal responses to their primary factors, as there were abrupt increases followed by relative stabilizations with NACA and TI increases; the crucial values between the two phases were about 45 ha of NACA and 9 million Yuan of TI (Fig. 2b and d). Technological factors such as the mechanized agricultural area (MAA) and land-leveling area (LLA) also had certain contributions (Fig. 2a and c).

For the 391 projects that involved land transfer, 37.01% of the total variation for (ln-) LRI was explained, with 7 factors that reflected technological efficiency (Fig. 2e). While the agricultural enterprise area (AEA) was the most important, as the AEA increased the marginal response showed rapid growth followed by a slow-down increment with stabilization of 11.50 of the (ln-) LRI value (Fig. 2e and f). Finally, the RF model explained 42.60% of the total variation for the (ln-) LI among the 1486 land consolidation projects with farmers involved in the construction, while the total investment (TI) primarily influenced the (ln-) LI (Fig. 2g). Similarly, the (ln-) LI of farmers increased abruptly (from 10 to 11) with the TI smaller than a critical value (of approximately 4 million Yuan), but when the TI increased beyond that, the change in (ln-) LI was relatively stable, with an amplitude of less than 0.20 (Fig. 2h). Other than the most important factors, the rest especially those for technological efficiency, generally made the responses of rural economic indicators abrupt (e.g. Fig. A1e, A2a and A3a), and even more complex than the marginal benefits of direct input factors (e.g. Fig. A2c, A4a and A4c).

3.2. Spatial-temporal patterns of the primary factors of regional rural economies

During the period of the sampled projects construction (2006–2016), the primary contributing factor of GPI was the NACA across the province in most years, with the R^2 in all cases higher than 50% (Fig. 3a, Table A1a). In the remaining years, the total area (TA) was the most important factor, highlighting the importance of direct inputs of agricultural production to GPI. For NAII during the period of 2006–2016, the early stage mainly emphasized the role of MAA, while TI was the dominant factor in the later stage (Fig. 3b, Table A1b). In addition, the primary factor of LRI in this region generally showed consensus among the years, and agricultural enterprise was important (Fig. 3c, Table A1c), except in 2006 and 2016, when a suitable model was unavailable (i.e., a negative R^2 occurred). For LI, however, the primary factor varied over the years, and the R^2 of the RF model was relatively small (Fig. 3d, Table A1d).

At the county scale, there were prominent spatial variations in the primary factors of the regional rural economies. In spite of some counties without a suitable model available, with over 50% of R^2 of the RF model in most counties, the factors reflecting the direct inputs of agricultural production dominated GPI, in particular the TA in southwestern counties, TI in northeastern counties, and NACA in central counties (Fig. 4a and b and Table A2a). In the northwestern counties of the province, the MAA was regarded as the primary factor, while the farm road length (FRL) dominated a few counties located along the coast (Fig. 4a). Likewise, the TA and TI were the most important to NAII in most counties, especially those in the center and southwest of the province (Fig. 4c and d and Table A2b). For the counties in northern Fujian, the technological components of land consolidation, MAA, and LLA primarily controlled NAII (Fig. 4c and d and Table A2b). Based on our samples, fewer than half of the counties in the province with land consolidation projects were involved in land transfer, resulting in far fewer counties with a suitable RF model of LRI (Fig. 4e and f and Table A2c). In most of these counties, the AEA was the primary factor of LRI, while technological factors such as the MAA

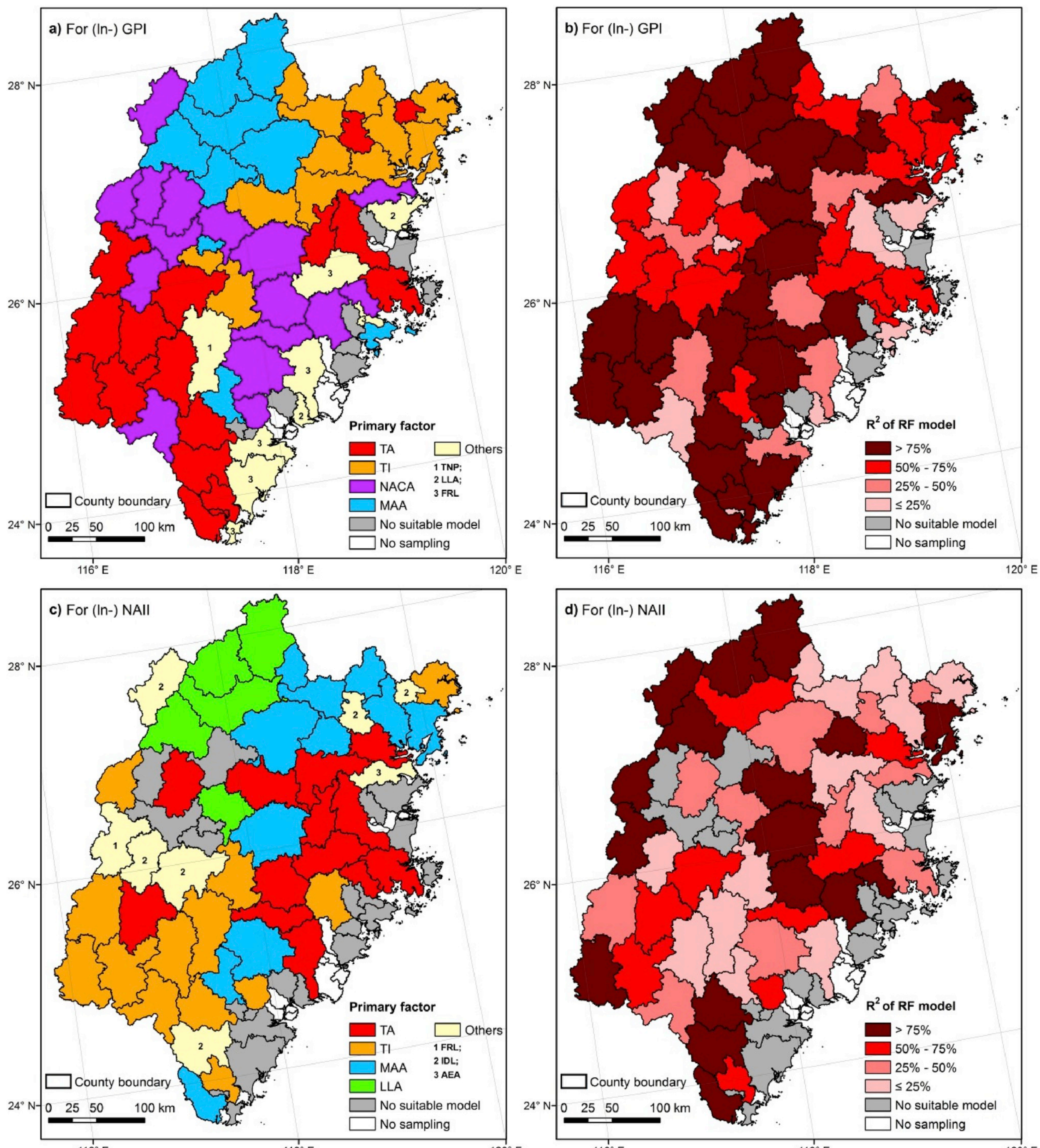

Fig. 4. The corresponding primary factors in the best random forest (RF) model among counties for a) (ln-) GPI, c) (ln-) NAII, e) (ln-) LRI, and g) (ln-) LI, while R^2 of the RF model in each county were shown in b), d), f), and h) respectively. Note that there were counties with project samples but not involving land transfer (LT) (Fig. e) and f)) or farmers' labor in constructions (FLC) (Fig. g) and h)).

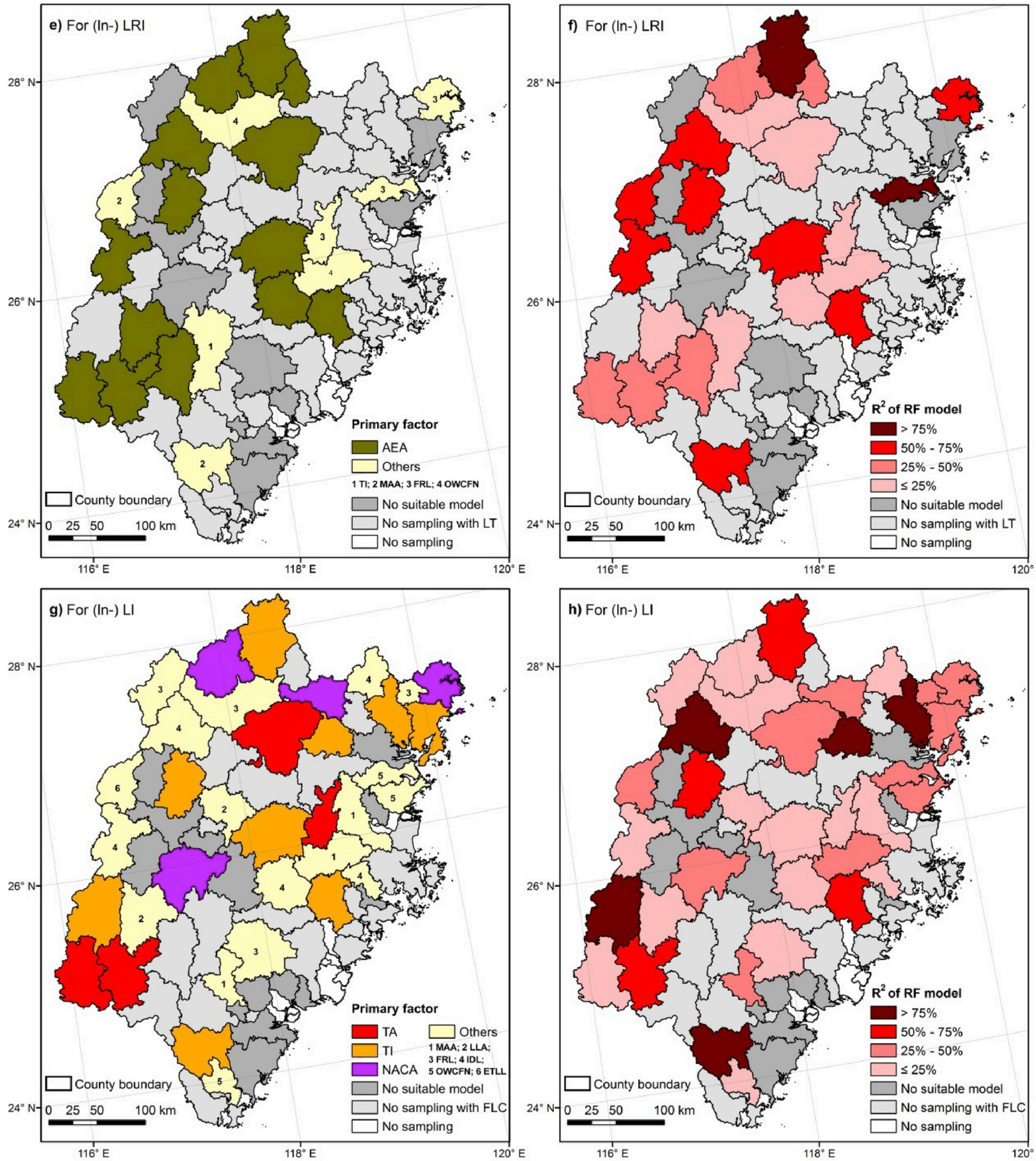

Fig. 4. (*continued*)

and FRL mainly dominated in the other counties (Fig. 4e and f and Table A2c). Finally, with regard to the sampled projects, 49 of 85 counties involved farmers' labor in project construction, and there were 35 counties with a suitable RF model of LI, while the most important factor varied disorderedly by county (Fig. 4g and h and Table A2d).

4. Discussions and conclusions

Because of its importance for increased cropland and food security, land consolidation has long been recognized as increasing grain yield (Monke et al., 1992). Land consolidation could also be an important tool for rural development, increasing land use efficiency, and labor productivity (Bonner, 1987), while agricultural land defragmentation and rural spatial restructuring through land-leveling and other measures were considered effective approaches (Crecente et al., 2002; Niroula and Thapa, 2005; Hartvigsen et al., 2012; Jia and Petrick, 2014; Long, 2014). Further, in this study, we directly distinguished each contributing factor, including the components of direct inputs for agricultural production and those of technological efficiency, to reveal the economic benefits of land consolidation.

Zhang and Zhang (2014) showed that the total area and investment in rural land consolidation could affect the agricultural macroeconomy. Similarly, for regional rural economies, our study indicates that the dominant contributions were made by factors reflecting the direct inputs, especially newly added cropland area (for GPI) and total investment (for NAII) (Fig. 2a and c). These contributions were generally uniform over time (Fig. 3a and b), while the two rural economic indicators (viz., grain production and net agricultural income) were related to inter-annual agricultural production conditions (Verón et al., 2004; Latiri et al., 2010; Guo et al., 2012; Karlberg et al., 2015). The results indicate that the other characteristics of agricultural production changed little over the years of the study period. By contrast, the production conditions and the causal mechanism of land consolidation varied with counties (Fig. 4a and c), making the specific survey and the corresponding project design significant in practice. Meanwhile, the importance of some engineering measures emerged, especially land-leveling measures in the north and northwest, the core areas of Wuyi Mountain. Wang et al. (2019) suggested that little available cropland resources in these areas made technological measures relatively important to improve land quality and thus promote grain production. A larger mechanized agricultural area was also considered necessary to raise rural household income and maintain national rice production levels in China (Van den Berg et al., 2005). Additionally, in land consolidation projects, land transfer directly accompanied agricultural enterprise (Lerman and Cimpoieş, 2006), which therefore has positive effects on LRI. However, the long-term impact of land transfer on soil quality and the rural economies required further investigation (Lyu et al., 2019). Moreover, in relation to agricultural enterprise as the primary factor, there was homogeneity among the years and in most counties (Figs. 3c and 4e), implying little spatial-temporal difference in agricultural land transfer price in Fujian during the study period. By contrast, the factors affecting the price of local labor in project construction must be complex (Figs. 2g, 3d and 4g).

On the basis of agriculture production theory, Hiironen and Riekkinen (2016) used economic growth records from 13 regions with land consolidation projects in Finland to demonstrate the benefits of such projects, such as saving production time and reducing production costs. Importantly, they suggested that the cost–benefit relationship was well suited for large datasets in project-level analysis. Based on this, in our study, as the direct input factors dominant for agricultural production, their marginal benefits all showed phases of rapid growth to stabilization and saturation with the optimum size of input (Fig. 2), following the law of diminishing marginal returns. Although the average values of these production factors across the study area stayed at the increasing phases in terms of marginal response, natural constraints made it impracticable to simply rely on the input scale to develop agriculture in the mountainous and hilly areas, compared to in flat areas. For example, the average values of both the total area and newly added cropland area in Fujian (31.19 ha and 5.66 ha, respectively) were much smaller than those in Heilongjiang (1896.58 ha and 163.05 ha, respectively) located in the Northeast China Plain, according to the China Land and Resources Almanac. Furthermore, with resource scarcity, these factors could not be practically expanded further in such rural areas (Liu et al., 2014), especially given the recent obvious decrease in newly added cropland from land consolidation in eastern China (Zhou et al., 2014). This meant that technological components must not be neglected. Among the four kinds of engineering measures, land-leveling was relatively important, due to the increment of effective cropland area and the reduction in land slope in mountainous and hilly areas, while erosion-control measures were generally less influential, possibly because of wide improvements to ecosystem services such as water and soil retention across this region over the past two decades (Ouyang et al., 2016). However, the marginal benefits of factors reflecting different technological components varied greatly and complexly (Fig. A1, A2, A3 and A4), with long-term monitoring and further exploring needed.

Currently, the new normal of China with the global economy development makes supply-side structural reform[3] more important than ever, especially the development and innovation of economic systems and technology in vast rural areas (Jiang and Du, 2017; Wang and Wei, 2017). Fortunately, in China, land consolidation implemented with project technology and innovations could promote the development of rural regions as the representative supply side (Liu et al., 2017; Hu et al., 2018), as also shown in this study. Different regions should further emphasize the characteristics of land consolidation according to regional conditions and local needs, such as building roads and other infrastructure to improve production efficiency, increasing mechanized agricultural areas to improve land quality, improving irrigation and drainage facilities to adapt to local water resource conditions, consolidating the whole farmland landscape to promote sustainable development, and introducing social capital such as agricultural enterprise to rural areas (Tang et al., 2017; Liu et al., 2018; Long et al., 2018). Meanwhile, based on the costs for rural developments through land consolidation (e.g. Table 1), we would like to remind the scarcity of cropland resources mentioned above, and that with ensuring the effectiveness, technological costs may need further reduction from the current conditions. Moreover, suggested that land consolidation is an organized government action with investments, for rural developments, land consolidation could not yet replace agricultural production in the long term. It must be stressed accompanied by improvements in breeding and cropping systems (Asfaw et al., 2012; Khan et al., 2014; Gaudin et al., 2015), rather than implementing land consolidation once and for all, to promote grain yields and agricultural income. Only in those ways, could the reasonable consideration and arrangement of land consolidation and its components (e.g., technological factors) be significant to driving locally endogenous growth in rural economies, especially in mountainous and hilly areas (Tian et al., 2010; Fan et al., 2012; Janus et al., 2017).

Further research and surveys may be conducted to reveal corresponding issues. First, the influential mechanisms of land consolidation are heterogeneous among regions, and a more detailed explanation for each area should be given, with especial consideration of the role of technological components. Second, land consolidation is generally accompanied by changes in local farming practices, such as fertilization and chemical plant protection (Hiironen and Riekkinen, 2016), so these activities must be quantitatively integrated in the mechanism. Third, the natural and social conditions in flat areas are importantly different from those in mountainous and hilly areas. As such, the corresponding influential mechanisms should be analyzed and compared. Thus, we can obtain more valuable information for project planning and designing effective land consolidation, to optimize institutional construction, and to make much contribution to regional rural development in the future.

[3] Supply-side structural reform was proposed in China in 2015, with aim at adjusting economic structure, and making the factors including labor, land, capital and innovation optimal allocate.

Table A1

The importance of each factor represented by the increase of mean square errors (IncMSE (%)) of OOB data in the best random forest (RF) models for a) (ln-) GPI, b) (ln-) NAII, c) (ln-) LRI, and d) (ln-) LI over years, while symbol '–' indicated that there was no this factor in the corresponding model, and noting that no suitable RF model for (ln-) LRI in 2006 and 2016.

a)

Year	TA	TI	TNP	NACA	MAA	LLA	FRL	IDL	OWCFN	ETLL	SFTN	ECA	AEN	AEA
2006	25.09	–	6.52	19.22	–	–	10.70	10.44	–	–	0.00	–	–	–
2007	18.08	12.04	3.35	15.67	10.93	14.76	13.19	–	–	–	0.00	6.39	–	–
2008	–	–	7.15	33.49	10.72	18.45	12.83	17.23	–	–	–	–	–	–
2009	–	–	19.20	33.66	23.95	27.47	–	–	19.00	–	–	15.67	–	–
2010	22.64	25.57	16.25	31.95	22.24	21.17	–	–	–	–	–	–	–	–
2011	–	21.28	11.95	39.45	22.61	32.39	–	–	12.98	–	5.14	12.30	–	8.91
2012	31.33	40.20	24.71	41.71	–	24.64	–	18.57	20.59	–	–	10.42	4.20	–
2013	–	35.14	27.17	45.94	31.14	30.36	22.56	16.52	21.90	–	–	–	–	–
2014	36.18	22.63	18.64	35.17	21.91	–	–	22.80	–	–	–	–	3.01	8.92
2015	–	14.51	9.64	38.30	21.52	19.74	12.37	7.14	–	2.60	–	1.61	2.53	2.26
2016	30.65	20.45	16.72	31.34	–	–	–	16.55	11.10	0.43	–	–	3.15	4.05

b)

Year	TA	TI	TNP	NACA	MAA	LLA	FRL	IDL	OWCFN	ETLL	SFTN	ECA	AEN	AEA
2006	–	15.77	–	–	29.40	–	17.64	11.18	–	0.00	–	–	5.65	–
2007	17.91	–	–	–	45.14	–	–	–	–	–	–	–	–	–
2008	–	19.68	–	15.64	25.89	17.70	15.09	12.79	–	–	–	–	–	–
2009	–	24.09	–	12.46	21.67	13.02	14.91	–	–	–	–	2.18	–	7.01
2010	20.98	–	–	15.51	21.79	20.48	7.16	3.68	–	0.00	0.00	3.79	–	–
2011	–	22.39	–	30.62	36.45	28.00	–	25.57	8.80	–	–	0.04	3.50	5.60
2012	28.87	47.58	–	–	25.21	21.29	19.90	–	20.99	–	–	1.10	5.65	8.32
2013	29.54	36.78	–	21.95	24.56	16.75	20.01	18.81	–	2.69	2.94	3.10	3.44	5.45
2014	–	51.55	–	24.25	35.70	28.40	20.12	24.57	13.57	0.00	–	–	–	9.06
2015	–	48.38	–	21.72	17.68	26.46	16.78	19.00	9.71	–	–	–	–	–
2016	–	27.83	–	–	36.45	46.35	16.64	25.17	8.97	0.87	0.00	–	8.52	11.69

c)

Year	TA	TI	TNP	NACA	MAA	LLA	FRL	IDL	OWCFN	ETLL	SFTN	ECA	AEN	AEA
2006	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2007	–	–	–	–	–	–	–	–	–	–	–	–	–	17.58
2008	–	0.34	–	–	6.67	–	–	–	0.00	–	–	1.48	0.00	8.38
2009	–	3.67	–	–	–	–	–	3.94	–	–	2.91	6.22	1.64	18.54
2010	11.65	–	–	9.09	8.00	–	–	–	7.10	0.00	–	4.54	–	5.44
2011	–	3.91	–	–	9.71	–	11.22	8.51	–	0.00	–	–	–	15.15
2012	–	–	–	–	–	8.11	–	–	13.03	–	1.99	5.71	14.16	22.22
2013	–	14.32	–	–	–	16.21	–	–	–	–	–	–	–	26.03
2014	–	–	–	3.84	–	–	–	–	2.71	0.00	–	3.16	–	4.81
2015	–	–	–	–	–	–	–	–	–	–	–	–	27.80	–
2016	–	–	–	–	–	–	–	–	–	–	–	–	–	–

d)

Year	TA	TI	TNP	NACA	MAA	LLA	FRL	IDL	OWCFN	ETLL	SFTN	ECA	AEN	AEA
2006	17.16	17.26	–	–	19.03	–	–	17.33	0.00	–	–	–	5.55	–
2007	8.45	–	–	–	–	–	–	–	–	0.00	–	–	3.63	–
2008	–	9.32	–	–	–	–	–	10.29	–	–	–	–	–	–
2009	–	–	–	–	–	19.81	16.39	6.12	–	3.48	4.27	14.76	–	–
2010	–	15.95	–	–	16.86	–	–	12.39	14.19	0.00	–	–	–	9.41
2011	–	22.07	–	–	33.02	–	16.44	23.66	16.29	–	4.67	5.05	2.24	8.96
2012	26.73	30.83	–	17.46	–	–	–	21.61	15.60	–	5.09	0.35	9.16	6.79
2013	–	29.36	–	26.94	–	–	–	35.31	–	–	–	–	–	–
2014	17.41	32.95	–	–	11.80	13.31	–	–	–	–	–	0.00	–	17.95
2015	–	13.73	–	–	9.84	11.48	23.85	–	6.30	0.00	0.00	0.55	–	–
2016	–	17.07	–	–	15.60	27.55	18.83	5.28	15.28	0.00	–	–	9.27	12.25

Table A2
The importance of each factor represented by the increase of mean square errors (IncMSE (%)) of OOB data in the best random forest (RF) models for a) (ln-) GPI, b) (ln-) NAII, c) (ln-) LRI, and d) (ln-) LI among counties, while symbol '–' indicated that there was no this factor in the corresponding model, noting that no suitable RF model where all factors with symbol '–' for the county.

a)

County	TA	TI	TNP	NACA	MAA	LLA	FRL	IDL	OWCFN	ETLL	SFTN	ECA	AEN	AEA
Anxi	9.54	9.21	–	9.93	9.02	–	–	–	5.54	–	–	–	0.00	0.00
Changle	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Changshan	3.37	–	–	0.00	–	–	0.00	2.70	0.00	–	–	–	–	–
Changtai	17.12	–	7.41	18.40	–	12.46	–	–	5.38	–	–	0.00	–	–
Changting	25.90	24.97	8.88	22.05	25.84	–	–	16.72	16.05	–	–	–	5.83	–
Chengxiang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Datian	–	22.73	–	16.68	18.56	–	–	–	–	–	–	–	–	–
Dehua	–	5.89	–	6.14	4.87	–	–	–	4.83	–	–	–	–	–
Dongshan	13.93	–	–	–	–	–	14.43	–	–	–	–	–	–	–
Fuan	–	25.50	10.08	–	–	17.42	13.62	14.28	–	–	–	18.28	0.00	–
Fuding	19.79	27.33	–	19.44	14.57	–	14.31	–	–	0.00	–	–	–	–
Fuqing	32.70	–	–	16.44	6.38	–	–	–	7.68	7.70	–	4.78	–	–
Gutian	22.34	24.44	–	–	23.17	–	–	–	–	–	–	–	–	–
Guangze	–	19.43	–	32.13	–	–	–	–	–	–	–	–	–	–
Hanjiang	–	3.07	5.25	15.38	–	12.45	4.24	–	–	0.00	–	8.04	–	–
Huaan	–	–	–	–	30.89	–	–	–	–	–	–	–	–	–
Huian	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Jianning	11.40	–	11.30	15.63	–	11.25	15.38	–	0.00	1.92	3.04	–	–	5.37
Jian'ou	29.17	–	–	34.38	35.15	–	11.72	–	–	0.00	–	–	0.92	–
Jianyang	20.35	–	11.54	18.24	20.83	–	–	–	8.62	–	–	–	–	7.26
Jiangle	–	–	–	17.98	17.04	15.32	–	–	–	–	–	14.68	6.56	1.82
Jiaocheng	–	29.45	–	28.44	–	–	–	–	–	–	–	–	–	–
Jin'an	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Licheng	0.00	–	–	0.00	–	0.00	7.23	–	–	–	–	–	–	–
Liancheng	40.81	16.30	29.98	–	–	–	13.43	–	–	2.15	–	–	8.15	–
Lianjiang	2.05	–	–	–	1.98	4.42	–	1.59	–	0.00	0.00	0.00	0.00	–
Longhai	0.00	–	–	0.00	0.00	–	4.72	–	–	0.00	0.00	0.00	0.00	0.00
Longwen	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Luoyuan	–	17.86	–	21.74	–	–	–	–	–	–	–	–	–	–
Mawei	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Meilie	0.00	0.00	0.00	–	3.88	0.00	0.00	–	–	–	–	0.00	–	0.00
Minhou	8.89	–	–	7.75	–	0.00	–	–	–	0.00	–	–	–	–
Minqing	25.39	–	–	–	–	–	–	–	–	–	–	–	–	–
Mingxi	–	–	8.38	12.04	–	–	–	–	–	–	–	10.15	–	8.21
Nan'an	–	–	–	–	–	4.68	15.77	–	–	–	–	–	–	–
Nanjing	15.17	–	12.66	15.13	–	10.03	10.40	–	–	–	–	–	–	–
Ninghua	32.30	–	–	–	20.88	–	–	–	–	–	–	–	–	–
Pinghe	23.35	–	11.98	18.49	20.18	–	–	14.24	–	–	–	–	5.45	–
Pingtan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pingnan	15.16	28.07	11.52	–	16.39	–	–	16.69	9.38	0.00	0.00	0.00	–	–
Pucheng	–	–	–	25.41	26.53	20.44	–	–	–	–	–	–	–	–
Qingliu	–	–	–	16.17	13.61	–	13.84	–	6.77	–	–	–	–	–
Quangang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sanyuan	–	14.88	–	–	–	–	–	–	–	–	–	–	–	–
ShaXian	–	5.98	8.66	10.33	7.45	–	–	10.33	0.00	–	–	–	–	–
Shanghang	38.74	18.40	19.87	29.83	–	–	–	–	–	–	–	–	1.42	3.36
Shaowu	15.31	11.44	–	11.02	15.72	11.68	8.72	–	–	0.00	0.00	3.12	–	–
Shouning	13.97	16.27	–	15.45	11.36	10.15	–	6.91	9.04	–	–	–	–	–
Shunchang	–	9.61	–	1.87	12.87	–	–	–	–	–	–	9.39	0.00	0.00
Songxi	–	29.70	–	–	–	–	–	–	–	–	–	–	–	–
Taining	–	2.49	5.40	6.56	–	–	–	–	–	0.00	–	–	6.38	–
Tongan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wuping	26.19	17.88	–	26.07	–	–	–	–	16.21	–	–	–	–	–
Wuyishan	–	–	–	23.55	24.61	19.23	–	–	–	–	–	–	–	–
Xiapu	–	38.28	–	19.41	16.65	14.89	–	–	–	–	–	–	3.02	5.74
Xianyou	26.01	14.29	–	33.41	–	–	15.07	12.29	3.43	0.00	0.00	–	–	10.03
Xiangcheng	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Xiang'an	–	–	3.61	–	3.49	6.97	–	–	–	–	0.00	–	–	–
Xinluo	10.05	–	9.56	–	6.15	–	–	–	–	–	–	–	–	–
Xiuyu	–	–	–	0.00	5.20	–	3.34	–	0.00	0.00	1.96	–	0.00	–
Yanping	23.74	25.63	–	16.58	–	–	–	–	–	–	–	–	–	–
Yongan	17.55	–	–	–	–	16.15	–	–	–	–	–	–	–	9.09
Yongchun	–	22.80	–	37.01	–	–	–	–	–	–	–	–	–	–
Yongding	14.95	–	11.78	23.56	–	–	–	–	–	–	–	–	–	–
Yongtai	–	–	14.59	–	–	–	18.00	–	–	–	–	–	10.22	–
Youxi	20.75	17.79	13.47	22.89	16.30	–	–	–	–	–	–	10.97	–	–
Yunxiao	49.69	–	–	–	–	–	–	–	–	–	–	–	–	–
Zhangping	16.83	17.81	22.89	16.39	–	19.73	–	–	–	–	–	0.00	–	–
Zhangpu	0.00	–	–	–	0.00	0.00	6.80	–	–	–	–	–	–	–

(continued on next page)

Table A2 (*continued*)

a)

County	TA	TI	TNP	NACA	MAA	LLA	FRL	IDL	OWCFN	ETLL	SFTN	ECA	AEN	AEA
Zhaoan	52.80	–	–	–	–	–	–	–	–	–	–	–	–	–
Zherong	16.90	12.51	–	12.03	–	–	–	–	–	–	–	–	–	–
Zhenghe	–	15.77	–	15.17	–	–	11.35	10.55	5.53	–	0.00	–	–	–
Zhouning	18.93	14.53	–	–	17.83	–	–	–	–	–	–	–	–	–

b)

County	TA	TI	TNP	NACA	MAA	LLA	FRL	IDL	OWCFN	ETLL	SFTN	ECA	AEN	AEA
Anxi	0.00	0.00	–	–	4.47	0.00	–	–	0.00	0.00	0.00	–	–	–
Changle	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Changshan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Changtai	–	10.73	–	9.53	9.12	–	–	5.92	1.11	0.00	0.00	0.00	3.42	3.69
Changting	20.51	25.83	–	–	17.90	–	15.07	–	–	0.00	–	–	2.11	11.49
Chengxiang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Datian	–	15.51	–	–	–	–	0.90	–	9.68	–	–	–	–	–
Dehua	14.69	11.63	–	–	14.39	3.42	8.52	9.79	–	–	–	–	–	0.72
Dongshan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fuan	–	–	–	7.53	8.68	–	–	5.06	–	0.00	0.00	0.00	–	–
Fuding	–	13.60	–	–	–	–	8.34	–	–	–	–	–	0.02	–
Fuqing	10.59	–	–	–	0.00	5.87	9.19	–	–	0.01	0.00	4.57	–	–
Gutian	11.37	–	–	–	–	–	9.75	–	–	–	–	–	–	–
Guangze	–	–	–	13.60	–	–	–	14.93	13.09	–	–	–	–	–
Hanjiang	21.03	–	–	–	–	–	–	–	–	–	–	19.39	–	–
Huaan	–	2.27	–	–	4.27	–	2.68	2.67	0.00	0.00	0.00	–	–	–
Huian	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Jianning	–	20.91	–	–	11.78	–	19.73	14.66	–	–	7.80	–	–	12.10
Jian'ou	–	–	–	10.64	32.09	–	–	–	18.69	0.00	–	0.00	13.61	–
Jianyang	–	–	–	16.44	15.85	16.50	–	13.74	–	–	–	–	–	11.35
Jiangle	20.95	–	–	16.61	–	–	–	–	–	–	–	–	6.17	–
Jiaocheng	12.85	–	–	12.33	–	–	–	–	–	–	–	–	–	–
Jin'an	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Licheng	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Liancheng	22.13	11.77	–	13.22	–	16.20	8.61	9.71	–	2.06	–	–	0.00	0.00
Lianjiang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Longhai	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Longwen	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Luoyuan	–	–	–	–	–	11.52	–	–	–	–	–	–	–	14.96
Mawei	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Meilie	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Minhou	7.24	5.65	–	–	–	–	5.29	4.77	–	–	–	–	–	–
Minqing	10.73	10.10	–	–	–	–	–	–	9.79	–	–	–	–	–
Mingxi	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Nan'an	4.31	0.00	–	–	–	0.00	0.00	0.00	–	0.00	–	–	–	–
Nanjing	11.36	12.57	–	11.40	11.84	1.66	6.39	–	0.00	0.00	0.00	0.00	0.00	0.00
Ninghua	–	39.63	–	–	–	–	50.44	–	–	–	–	–	–	–
Pinghe	–	–	–	–	15.29	12.09	8.75	21.24	8.97	0.00	0.00	19.47	6.91	8.34
Pingtan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pingnan	–	–	–	–	49.51	–	–	–	–	–	–	–	–	–
Pucheng	–	21.43	–	19.09	–	23.44	18.36	–	–	–	–	–	–	–
Qingliu	–	–	–	–	5.46	–	–	8.33	–	0.00	–	0.00	0.00	1.00
Quangang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sanyuan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ShaXian	6.15	0.00	–	–	–	7.03	–	–	–	–	–	–	–	–
Shanghang	34.53	44.31	–	28.97	–	17.10	–	–	11.64	–	–	–	–	5.36
Shaowu	–	–	–	–	18.23	19.14	9.68	11.52	8.22	0.00	–	6.55	–	–
Shouning	–	–	–	–	4.57	4.44	–	–	3.36	–	–	–	–	–
Shunchang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Songxi	–	–	–	–	3.74	0.00	–	–	0.35	–	–	–	–	–
Taining	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Tongan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wuping	–	20.93	–	–	18.53	18.92	–	11.50	14.35	–	–	–	12.89	15.20
Wuyishan	–	13.02	–	19.04	–	19.67	–	12.46	–	–	–	0.00	–	9.10
Xiapu	15.98	17.74	–	–	17.77	–	–	–	–	–	–	–	–	–
Xianyou	31.59	53.99	–	–	–	21.71	–	20.89	15.43	–	–	–	–	11.92
Xiangcheng	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Xiang'an	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Xinluo	–	5.71	–	4.92	–	–	–	–	–	0.00	0.00	–	1.23	4.59
Xiuyu	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Yanping	48.01	–	–	–	–	–	–	–	–	–	–	–	–	–
Yongan	–	–	–	–	–	0.00	–	12.71	–	–	–	–	–	–
Yongchun	23.77	17.76	–	–	–	3.87	–	14.28	2.56	0.00	–	–	–	–
Yongding	–	23.54	–	–	–	–	–	–	–	–	–	–	–	–

(*continued on next page*)

Table A2 (*continued*)

b)

County	TA	TI	TNP	NACA	MAA	LLA	FRL	IDL	OWCFN	ETLL	SFTN	ECA	AEN	AEA
Yongtai	11.46	10.37	–	4.99	–	0.00	–	10.51	–	0.00	–	–	–	–
Youxi	–	13.93	–	10.97	25.80	10.17	10.04	9.24	0.83	–	–	11.16	0.00	–
Yunxiao	–	33.63	–	–	–	–	–	–	–	–	–	–	–	–
Zhangping	–	19.08	–	–	–	–	–	–	–	–	–	–	–	12.83
Zhangpu	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Zhaoan	13.78	11.71	–	–	14.02	–	–	–	–	–	–	–	–	–
Zherong	–	–	–	–	–	–	–	13.64	–	–	–	–	–	–
Zhenghe	–	–	–	–	9.45	2.50	–	–	–	–	–	–	–	–
Zhouning	–	–	–	–	–	–	9.14	11.62	–	–	–	–	–	7.42

c)

County	TA	TI	TNP	NACA	MAA	LLA	FRL	IDL	OWCFN	ETLL	SFTN	ECA	AEN	AEA
Anxi	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Changle	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Changshan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Changtai	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Changting	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Chengxiang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Datian	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Dehua	–	–	–	0.00	–	0.00	0.00	–	0.00	0.00	0.00	–	0.00	0.14
Dongshan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fuan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fuding	–	–	–	–	–	9.81	10.46	–	–	–	–	–	–	–
Fuqing	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Gutian	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Guangze	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Hanjiang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Huaan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Huian	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Jianning	12.37	10.12	–	–	13.21	–	–	10.48	–	2.67	6.41	3.12	4.21	–
Jian'ou	–	–	–	–	–	5.32	–	–	–	–	–	–	–	6.70
Jianyang	–	–	–	–	–	–	–	–	10.27	–	–	–	–	–
Jiangle	9.29	–	–	–	–	–	–	–	–	–	–	–	7.46	9.52
Jiaocheng	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Jin'an	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Licheng	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Liancheng	–	–	–	–	–	–	3.99	–	–	–	–	–	–	10.64
Lianjiang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Longhai	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Longwen	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Luoyuan	–	–	–	–	–	–	12.77	12.76	–	–	–	–	–	11.84
Mawei	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Meilie	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Minhou	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Minqing	0.00	–	–	–	0.00	–	3.63	–	–	0.00	0.00	0.00	–	–
Mingxi	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Nan'an	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Nanjing	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ninghua	–	–	–	–	–	–	–	–	–	–	–	–	–	21.91
Pinghe	–	–	–	–	14.00	–	–	–	–	–	–	–	–	10.90
Pingtan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pingnan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pucheng	–	–	–	12.24	14.12	–	–	14.72	–	–	–	–	–	15.66
Qingliu	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Quangang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sanyuan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ShaXian	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Shanghang	–	–	–	–	0.00	–	–	–	–	–	–	–	–	11.36
Shaowu	–	2.79	–	–	–	–	10.52	–	–	–	–	–	–	12.78
Shouning	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Shunchang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Songxi	–	–	–	7.19	–	–	–	–	–	–	–	–	–	10.25
Taining	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Tongan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wuping	–	0.29	–	–	3.98	10.88	–	6.66	–	0.00	–	–	–	16.48
Wuyishan	–	–	–	–	–	–	–	–	–	–	–	–	–	14.93
Xiapu	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Xianyou	–	–	–	–	–	–	–	–	–	–	–	–	–	17.79
Xiangcheng	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Xiang'an	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Xinluo	–	–	–	–	8.45	–	–	–	–	–	–	–	–	14.10

(*continued on next page*)

Table A2 (*continued*)

c)

County	TA	TI	TNP	NACA	MAA	LLA	FRL	IDL	OWCFN	ETLL	SFTN	ECA	AEN	AEA
Xiuyu	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Yanping	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Yongan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Yongchun	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Yongding	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Yongtai	0.00	–	–	–	–	–	–	–	2.64	–	–	–	–	–
Youxi	–	–	–	–	–	–	–	–	–	–	–	–	–	22.68
Yunxiao	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Zhangping	–	9.71	–	–	–	–	–	–	–	–	–	–	–	–
Zhangpu	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Zhaoan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Zherong	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Zhenghe	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Zhouning	–	–	–	–	–	–	–	–	–	–	–	–	–	–

d)

County	TA	TI	TNP	NACA	MAA	LLA	FRL	IDL	OWCFN	ETLL	SFTN	ECA	AEN	AEA
Anxi	–	–	–	0.00	–	–	4.67	–	0.00	–	–	–	0.00	0.00
Changle	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Changshan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Changtai	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Changting	–	62.75	–	–	–	–	–	18.74	–	–	–	–	–	–
Chengxiang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Datian	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Dehua	–	–	–	–	–	–	–	10.90	–	–	–	–	–	10.56
Dongshan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fuan	–	39.71	–	–	–	–	22.48	–	–	–	–	–	–	–
Fuding	–	–	–	13.31	–	–	–	–	–	–	–	–	–	12.10
Fuqing	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Gutian	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Guangze	0.00	0.00	–	–	0.00	0.00	2.01	–	0.00	0.00	0.00	0.00	0.00	0.00
Hanjiang	0.00	–	–	0.00	0.00	0.00	–	2.66	0.00	–	–	–	–	–
Huaan	–	–	–	–	10.69	–	–	–	–	–	–	–	–	–
Huian	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Jianning	–	7.75	–	–	7.35	–	–	8.86	–	13.27	–	–	8.99	–
Jian'ou	20.26	18.28	–	–	12.28	17.75	–	–	10.13	0.00	–	–	–	–
Jianyang	–	–	–	–	–	–	8.46	–	–	–	–	0.00	–	–
Jiangle	–	12.72	–	–	–	–	–	9.43	–	–	–	–	–	9.96
Jiaocheng	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Jin'an	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Licheng	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Liancheng	–	–	–	–	–	3.64	–	–	–	0.00	–	–	–	–
Lianjiang	0.00	0.00	–	0.00	–	–	–	0.00	1.56	0.00	–	–	–	–
Longhai	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Longwen	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Luoyuan	–	–	–	–	–	–	–	–	16.20	–	–	–	9.57	–
Mawei	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Meilie	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Minhou	7.68	–	–	–	8.28	–	–	–	4.93	0.00	–	–	–	–
Minqing	1.38	–	–	–	–	0.00	–	–	–	0.00	0.00	0.00	–	–
Mingxi	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Nan'an	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Nanjing	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ninghua	–	–	–	–	–	–	–	0.29	–	0.00	–	–	–	–
Pinghe	–	56.20	–	–	–	–	–	21.91	–	–	–	–	–	–
Pingtan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pingnan	–	50.72	–	–	–	–	–	–	–	–	–	–	–	–
Pucheng	25.84	31.96	–	–	–	–	18.90	–	–	–	–	–	–	–
Qingliu	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Quangang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sanyuan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ShaXian	–	–	–	–	–	7.76	–	6.11	–	–	–	–	–	–
Shanghang	26.02	–	–	–	–	–	–	10.76	–	–	–	–	–	–
Shaowu	14.79	13.27	–	13.02	–	–	11.33	14.99	–	–	0.00	–	–	–
Shouning	–	–	–	1.54	–	3.30	–	3.44	–	0.00	0.00	0.00	–	0.00
Shunchang	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Songxi	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Taining	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Tongan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wuping	5.47	–	–	–	5.06	–	–	–	–	–	–	0.00	0.00	–
Wuyishan	–	–	–	4.96	–	–	2.56	1.11	–	0.00	–	0.00	0.00	–

(*continued on next page*)

Table A2 (*continued*)

d)

County	TA	TI	TNP	NACA	MAA	LLA	FRL	IDL	OWCFN	ETLL	SFTN	ECA	AEN	AEA
Xiapu	–	10.41	–	–	–	–	9.93	–	8.54	–	–	–	0.73	–
Xianyou	7.67	44.75	–	–	–	–	12.90	10.11	0.00	0.00	–	–	–	–
Xiangcheng	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Xiang'an	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Xinluo	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Xiuyu	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Yanping	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Yongan	–	–	–	11.73	–	6.29	–	–	–	–	–	–	–	–
Yongchun	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Yongding	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Yongtai	–	–	–	–	9.09	–	6.08	–	–	–	–	–	–	–
Youxi	–	13.46	–	–	–	–	–	–	–	–	–	–	–	–
Yunxiao	0.00	0.00	–	–	–	0.00	0.00	0.00	1.41	0.00	0.00	0.00	–	–
Zhangping	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Zhangpu	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Zhaoan	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Zherong	–	–	–	–	–	–	11.95	–	–	–	–	–	–	–
Zhenghe	–	–	–	10.75	8.04	–	–	–	–	–	–	–	–	–
Zhouning	–	–	–	–	–	–	–	–	–	–	–	–	–	–

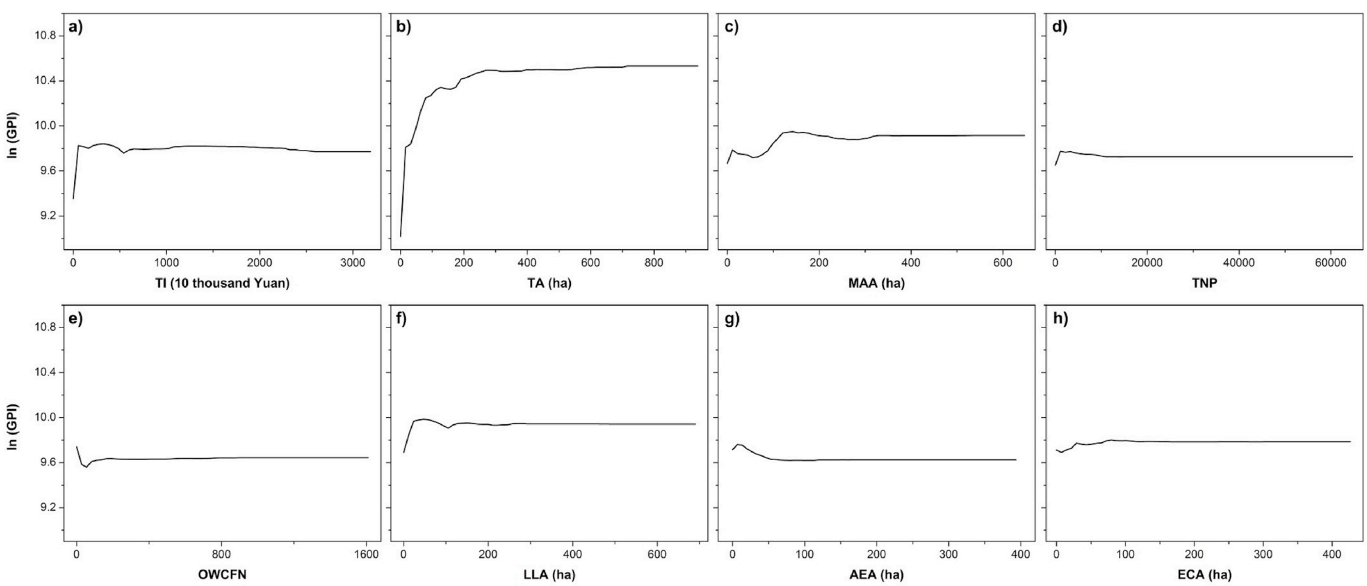

Fig. A1. Referring to Fig. 2a and b, the marginal response of (ln-) GPI to each factor other than the most important one in the corresponding best random forest models, showed with the partial dependence plot.

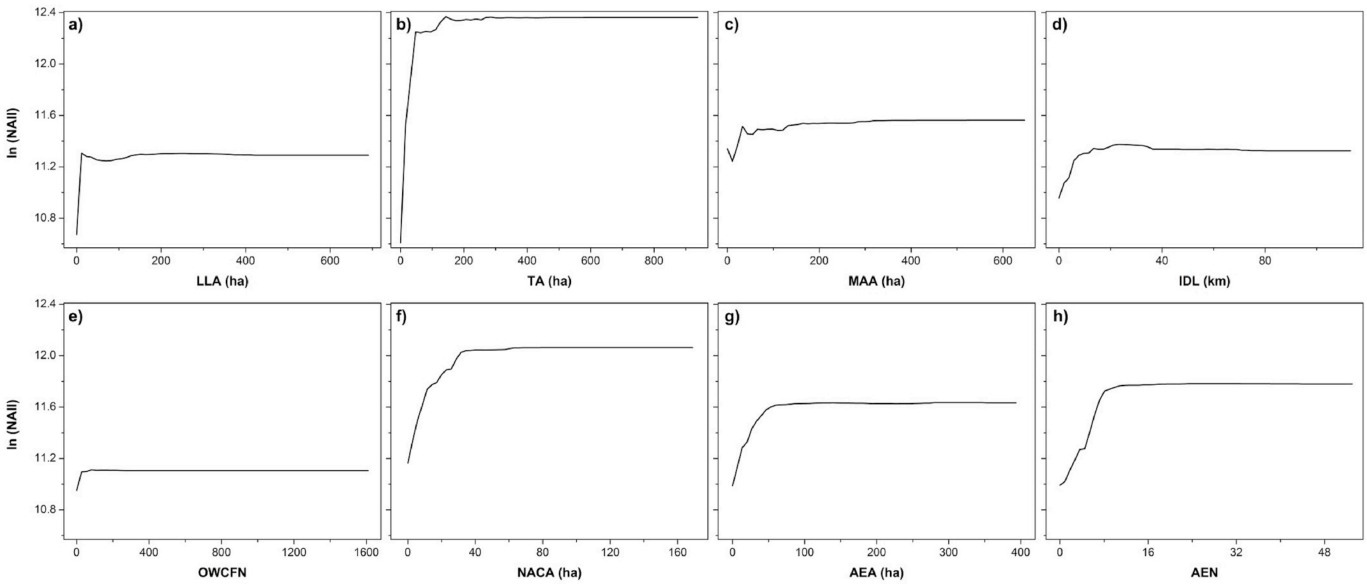

Fig. A2. Referring to Fig. 2c and d, the marginal response of (ln-) NAII to each factor other than the most important one in the corresponding best random forest models, showed with the partial dependence plot.

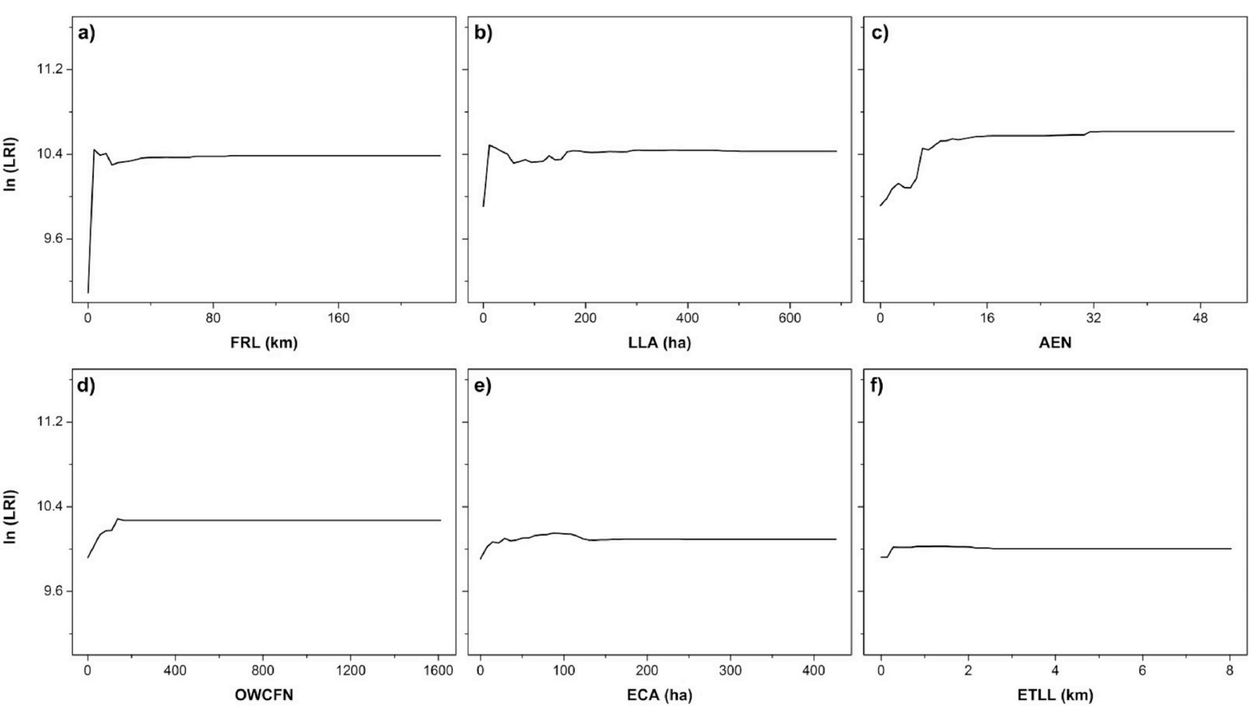

Fig. A3. Referring to Fig. 2e and f, the marginal response of (ln-) LRI to each factor other than the most important one in the corresponding best random forest models, showed with the partial dependence plot.

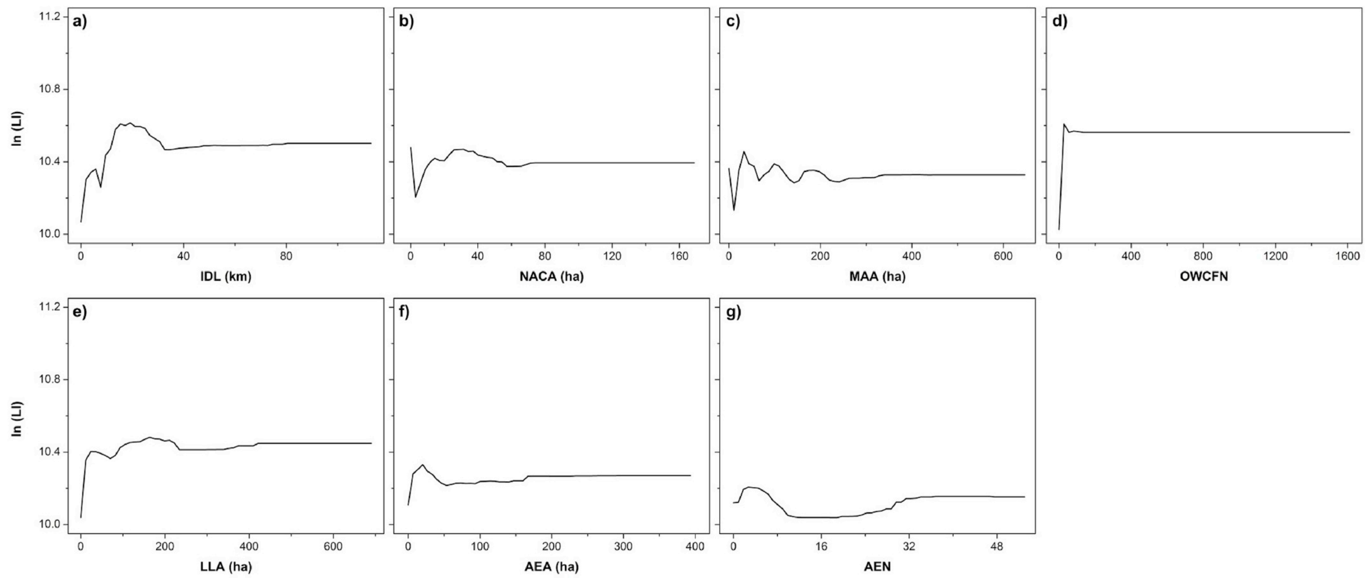

Fig. A4. Referring to Fig. 2g and h, the marginal response of (ln-) LI to each factor other than the most important one in the corresponding best random forest models, showed with the partial dependence plot.

CRediT authorship contribution statement

Lingxiao Ying: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing - original draft. **Zhanjie Dong:** Conceptualization, Investigation, Resources, Data curation. **Jun Wang:** Conceptualization, Resources, Writing - review & editing, Supervision, Funding acquisition. **Yachong Mei:** Methodology, Formal analysis. **Zehao Shen:** Methodology. **Yu Zhang:** Investigation.

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