

Land pressure evaluation in the Yangtze River Delta region: A perspective from production-living-ecology

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February 21, 2023

Abstract

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Abstract

The limited land is under unprecedented pressure from production, living and ecology. In order to evaluate the land pressure in the Yangtze River Delta region in 1995, 2000, 2005, 2010, 2015, and 2020 from the perspective of production, living, and ecology. This study builds a land pressure evaluation index system based on a fuzzy comprehensive evaluation model using multi-source and multi-scale data. In order to investigate trade-offs and synergies among production, living, and ecology pressures, we use the mechanical equilibrium model in physics. We then analyze land pressure model reliability and uncertainty using Monte Carlo simulations. The results show that (1) Our model can effectively reveal the level of land pressure and reflect the land pressure geographical pattern of "high in the east and low in the west, high in the south and low in the north" that characterizes the Yangtze River Delta region. (2) While living and ecology pressures are tending to rise, production pressures are tending to decrease. (3) Except for Shanghai, the trade-off areas are primarily concentrated in economically successful regions with high production and living pressure and low ecology pressure. The coordinated areas are primarily found in northern Jiangsu Province and northern Anhui Province.

Keywords: Land pressure; Production-living-ecology; Fuzzy comprehensive evaluation; Model validation; Yangtze River Delta region.

Introduction

For the continued existence of humans and for their ability to evolve, land serves as a crucial material foundation (Verburg et al., 2009; Jiang et al., 2022). People have increased from 2.6 billion in 1950 to 7.6 billion in 2021 as a result of increasing urbanization, and human activities are deteriorating the state of the land cover and ecological environments at an unprecedented rate, size, and spatial scale (Liu et al., 2014; Lazzarini et al., 2015; Nathaniel and Khan, 2020; Yu et al., 2021; Amponsah et al., 2022). The need to study and solve a variety of issues brought on by rising pressure on the land has been underlined (Zhu and He, 2010). With the rapid development of the economy and society, human demand for land resources is increasing, and the contradiction between humans and land is gradually accentuated and deteriorating (Herrmann et al., 2020; Pereira da Silva and Schwingel, 2021). The world's 6 million km² of protected land is already under a significant amount of pressure (Jones et al., 2018). Almost every city in the world, regardless of its size, is affected by land pressure, which is a result of the development of human society itself. Land use in different regions naturally presents different states and produces different effects, and changes with the change in land pressure as a result of the natural endowment of land resources in different regions and the pressure on economic development (Chen et al., 2021; Liu et al., 2022), food production (Jiang et al., 2018; Liu et al., 2020; Gao et al., 2022; Zhang et al., 2022), and ecological protection (Hao and Li, 2014; Chen et al., 2021; Liu et al., 2022; Zhao et al., 2022).

Population pressure (Herrmann et al., 2020; Mammides, 2020), urbanization pressure (Quang and Kim, 2020; Klusacek et al., 2022), and ecological pressure (Hirsh-Pearson et al., 2022) have been the main topics of academic research on land pressure. Early domestic studies calculated the pressure on cultivated land to analyze land pressure (Liu et al., 2020). As the research develops, an increasing number of academics are beginning to take into account the combined effects of numerous causes on land pressure (Yang et al., 2020; Lai et al., 2022) and to evaluate land pressure using diverse research scales, indicators, and methodologies (Cheng et al., 2011; Hao and Li, 2014; Chen et al., 2017; Han et al., 2020; Zhang and Dong, 2022). Currently, methods for measuring land pressure that are often used include gray correlation analysis, Shannon entropy, principal component analysis, and hierarchical analysis (Ou et al., 2017; Gupta et al., 2018; Hu and Xu, 2019; Lin et al., 2020; Zhang et al., 2021). While the principal component analysis and Shannon entropy methods have more objective evaluation results and the hierarchical analysis method is too subjective, all of these factors will have an impact on the accuracy and reliability of the evaluation results. For the comprehensive index method, the availability of data will limit the selection of some important indicators. Fuzzy evaluation techniques, as opposed to traditional methods, use fuzzy sets and fuzzy logic theory to evaluate complex things affected by multiple factors as a whole (Cai et al., 2019). This allows an indicator value to belong to multiple pressure levels with different affiliation degrees at the same time, reducing the influence of subjective and objective factors while better reflecting the actual characteristics of indicators (Sun et al., 2018; Zahabi

and Kaber, 2019). However, very few scholars have assessed land pressure using fuzzy evaluation methods from production-living-ecology aspects.

The Yangtze River Delta region (YRDR) is currently experiencing rapid urban expansion and faces potential risks from urbanization and natural disasters like climate change. The region is also economically developed, densely populated, and relatively concentrated in urban clusters (Pei et al., 2021; Yu et al., 2022). Scholars have mainly focused on issues such as land-intensive use (Luo et al., 2022), urban expansion (Luo and Lau, 2019), ecological efficiency (Li et al., 2022), ecological security (Xiaobin et al., 2021; Zhang et al., 2022), eco-environment pressure (Lin et al., 2020) in the YRDR, lacking research on land pressure. Over-exploitation has resulted in a sharp decline in the region's primary agricultural land and green ecological space, as well as a steadily worsening ecological environment. This has seriously hampered the overall sustainable development of the region's land area, and the problem of land pressure is particularly acute. The YRDR, one of China's most developed regions, will be essential in resolving the land pressure issue. The evaluation results are difficult to express accurately in the current studies, and there is a lack of quantitative analysis of land pressure based on the spatial scale of the grid. These studies, however, primarily concentrate on large-scale areas such as provinces, cities, counties, a few significant economic zones, and watersheds. Therefore, ensuring the sustainable use of land resources, assessing land pressure in the YRDR based on pertinent data research, analyzing the spatial distribution of land pressure in the YRDR, and exploring the synergistic and trade-off relationships of land pressure have become important needs for the sustainable development of the region.

We built a land pressure evaluation system using a fuzzy comprehensive evaluation method. Our specific goals are: (1) to evaluate the level of land pressure in each 1 km grid in the YRDR, (2) to characterize the spatial distribution of production, living, and ecology pressure and their tradeoff/synergy characteristics and (3) to verify the reliability and uncertainty of the land pressure evaluation model. Our findings offer a method for evaluating land pressure quantitatively from the perspective of urban agglomerations and have significant research ramifications for the sustainable use of land resources.

Materials and Methods

Study Area

The YRDR is comprised of 41 cities in Shanghai, Jiangsu Province, Anhui Province, and Zhejiang Province, which are distributed in the optimized and key development areas of the national "two horizontal and three vertical" urbanization pattern. It is situated at the intersection of two highly urbanized urban zones along the river and the coast of China (Figure 1). One of China's most economically active, urbanized, and population-absorbing areas, the Yangtze River Delta will contribute 24% of the nation's population and gross domestic product in 2021 (Qiao et al., 2021).

Figure 1. Study area: (a) location of the YRDR in China. (b) The 41 cities and economic zones in the YRDR. The abbreviations of city names refer to previous studies (Yu et al., 2022).

Data

We assessed land pressure in the YRDR using a variety of datasets, including data on land use, topography, socioeconomics, environmental, and fossil energy consumption from 1995 to 2020. All of the statistics utilized are yearly. Referring to previous studies, we selected a total of 22 indicators from the production, living, and ecology aspects, with P4, E3, E4, and E5 as negative indicators and the rest as positive indicators. Positive indicators indicate that the greater the indicator, the higher the land pressure, negative indicators indicate that the greater the indicator, the lower the land pressure (Yang et al., 2020; Jiang et al., 2021; Liu et al., 2022; Sun et al., 2022). Table S1 provides comprehensive explanations of the data sources used for the various study objectives.

Methods

Based on the fuzzy comprehensive evaluation method, this study evaluates land pressure in the YRDR from

three perspectives: production, living, and ecology pressure. It also examines the characteristics of land pressure's spatial and temporal distribution, identifies trade-offs and synergistic effects, and assesses the reliability of the evaluation model. Figure 2 displays the flow of the analysis.

Figure 2. Flowchart of the land pressure evaluation study

Developing the land pressure assessment model

The real output pressure on one side of the land that corresponds to human needs is known as land pressure (Zhu, 2010). By drawing on the index system of land evaluation research and combining the quantifiability and accessibility of data to evaluate land pressure, this study constructs an index system for quantitative assessment of land pressure by considering the demand for land in three aspects: production, living, and ecology.

Currently, most land pressure evaluation scales use large-scale research with cities as the evaluation units. However, these scales are unable to account for variations in land pressure within individual cities. As a result, the raster is chosen as the evaluation unit in this study, and the evaluation unit is ultimately decided to be 1km*1km. We transform the vector data into 1km resolution raster data for the indicators P1, P2, P3, P5, L2, L4, L5, L6, L8, L9, L10, E1, E2, E4, E6, and we resample the data into 1km resolution raster data for the indications P4, L3, L7, E3, and E5 using the ArcGIS resampling tool. To calculate the weights of the indicators using the index data scales, we choose the entropy weighting method (Wen et al., 2021; Dong and Lyu, 2022).

Land pressure comprehensive evaluation

The fuzzy comprehensive evaluation method uses fuzzy mathematical theory to produce an overall assessment of items exposed to various conditions. By using fuzzy association functions, inference rules, and defuzzification techniques, it translates qualitative assessment into quantitative evaluation and turns raw data values into output evaluation scores (Yu et al., 2020). Fuzzification, fuzzy inference, and defuzzification are the three processes that make up the fuzzy comprehensive assessment process (Cai et al., 2019).

Using the fuzzy inference system toolbox of the MATLAB program, we first design the Mamdani FIS model for each indicator and fuzzily the indicator values (Akbari et al., 2019). The Mamdani FIS model's deterministic input values are converted through a process called "fuzzification" into the equivalent fuzzy linguistic variables (e.g., land pressure levels). Production pressure, living pressure, and ecology pressure are divided into four levels using the natural fracture method: high pressure, medium pressure, low pressure, and very low pressure. Based on the intrinsic properties of the data, the natural fracture method can group data that have the most similarities.

Second, using the affiliation function and fuzzy inference rules, we get the fuzzy evaluation scores for each index. Positive indicators indicate that the greater the indicator, the higher the land pressure score, while a negative indicator is an opposite. The affiliation function is applicable to describe the fuzziness of things. According to earlier research, the S- and Z-shaped affiliation functions are best for defining fuzzy concepts with high and low-value fuzzy states, whereas the triangle affiliation function is best for explaining fuzzy concepts with intermediate fuzzy states (Ustaoglu and Aydinoglu, 2020). To create the affiliation functions of 22 indicators in 1995, 2000, 2005, 2010, 2015, and 2020 and convert the indicator data into affiliation degrees, we choose the triangular affiliation function, S-shaped affiliation function, and Z-shaped affiliation function (Figure S1). The affiliation value of the intersection of two adjacent affiliation functions is 0.5. To link the input and output variables for each indication, we build fuzzy inference rules. Finally, defuzzification based on the centroid approach is used to produce the fuzzy assessment score for each index, which provides smoother output inference control, and the output changes for tiny changes in the input data (Figure S2).

We weigh the comprehensive evaluation scores for each dimension in 1995, 2000, 2005, 2010, 2015, and 2020 before adding the scores for production pressure, living pressure, and ecology pressure to get the comprehensive evaluation scores for land pressure over the six years in the Yangtze River Delta.

where S represents the composite score of a dimension, for production pressure and ecology pressure dimension $q=6$, for living pressure dimension $q=10$, w_i and x_i represent the weight and fuzzy evaluation score of indicator i , respectively.

Tradeoff/synergy analysis based on Mechanical Equilibrium Model

The force balance model can be used to measure the coordination within the system (Zhang et al., 2019). In this study, the vector connection between three forces operating in opposing directions in the Cartesian coordinate system is used to abstract the production pressures, living pressure, and ecology pressure. The total vector forces and the quadrant in which they are positioned indicate the state and characteristics of the system under the impact of variously directed forces objectively.

The combined force is zero and is situated at the zero point in Figure 3, if all three forces succeed in achieving the intended outcome, signifying the coordinated growth of each subsystem. The three subsystems are in an unbalanced condition, as seen by the total force's deviation from point o in Figure 3.

The combined force F 's size may be used to gauge how much land pressures conflict with one another, and the higher the value of F , the less coordinated production pressure, living pressure, and ecology pressure are. The combined force's angle of deviation can indicate which of the three forces is the most prominent feature and can also reveal details about the coordination. In the model, the letters OA, OB, and OC stand for the pressures on production, ecology, and living, respectively. The angle between them is $2/3\pi$ (Yang et al., 2019). In the actual calculation, polar coordinates are used to represent the coordination state of land pressure. r is the polar radius to represent the coordination degree, and θ is the polar angle to represent the deviation direction.

In polar coordinates, the orientation angles of OA, OB, and OC are defined as $\pi/2$, $11\pi/6$, and $7\pi/6$, respectively. We determine the combined force of OA, OB, and OC and extend OA, OB, and OC in the other direction to split the area into six equal quadrants, as shown in Table S2. The calculation formulas are as follows:

where F_1 is the resultant force of OA and OB, α is the angle between F_1 and OA, F is the resultant force of F_1 and OC, and θ is the angle between F and X axis.

Figure 3. Conceptual model of production, living, and ecology pressure deviation levels

Monte Carlo simulation for validation

The Monte Carlo simulation method, also known as the stochastic simulation method, estimates the probability of an event occurring by the frequency of its occurrence (Yang et al., 2020). It is frequently utilized in numerous domains, including biology, sociology, and ecology (Ewertowska et al., 2017; Zaroni et al., 2019). To eliminate the uncertainty induced by weight selection, we utilized the Monte Carlo method to randomly simulate the weights of 22 land pressure indicators 1000 times. We created 1000 sets of indicator weights for the 22 land pressure indicators by utilizing the identified weights as means and 10% of the identified weights as standard deviations based on a normal distribution (Cheng et al., 2022). The land pressure fraction for each pixel in 2020 was calculated using a variety of indicators based on 1000 simulated weights. Finally, we express the uncertainty of each raster by calculating the 95% and 5% quartiles of the confidence interval of the land pressure scores, as well as the difference between them, as well as the variable ratio to the original assessment scores at the 90% confidence level, with higher uncertainty at higher values.

Results

Evaluation of production, living, and ecology pressure

The study of production, living, and ecology pressure in the YRDR improves understanding of land pressure disparities, which is conducive to focused measures to reduce land pressure in the YRDR. Figure 4 depicts the spatial and temporal changes in production, living conditions, and ecology constraints in the YRDR at five-year intervals from 1995 to 2020.

There were notable regional disparities in production pressure, with a general geographical pattern of high in the southeast and low in the northwest from 1995 to 2020. The majority of regions in the YRDR had medium to high levels of ecology pressure, with low-level areas mostly concentrated in the region's northwest in 1995. The initially continuously dispersed high-level locations in the northeast and southeast were sporadically distributed in 2000 as the low-level production pressure slowly migrated to those regions. The dispersed distribution of high-grade regions steadily showed a tendency of development along the coast, reaching the maximum expansion area in 2015, which included SH as well as the entirety of Zhejiang Province except HU from 2005 to 2010. The YRDR as a whole to HZ-SH as the dividing line pressure grade high and low distribution is obvious, and in the majority of the high-level locations in Zhejiang Province in 2020 pressure has reduced.

The southeast and province capitals had higher living pressure levels than the northwest, according to research from 1995 to 2020. With time, the region of high living pressure extends from a faceted scattered patchy distribution to a faceted concentrated continuous distribution, and the intensity of living pressure is rising. The strong provincial capital plan may have a role in the living pressure in HF in Anhui province, where the gap with other cities in the province is progressively rising. Living pressure is typically lower in northern Jiangsu and most of Anhui Province due to less intense agricultural, social, and economic activities, in contrast to the generally increasing trend of living pressure in southern Jiangsu Province and Zhejiang Province.

The YRDR's northwest and central-east region experience high ecology pressure and ecology pressure are typically stronger in the north than in the south. As urbanization progresses, the high-grade areas exhibit a pattern of progressive growth. It is important to note that in the high-level region, typical resource-based cities like XZ, HN, and HB as well as economically developed regions like NJ, JX, and SH are constantly under greater ecology pressure. However, the pressure in SH and NJ has significantly decreased over the past five years. The cities of FY, BZ, SQ, CA, SU, and YC eventually develop into others that are under high ecology pressure.

Figure 4. Production, living, and ecology pressure spatial distributions in the YRDR in 1995, 2000, 2005, 2010, 2015, and 2020

Spatial distribution of land pressure

The land pressure in the YRDR is divided into five categories based on the results of the research: slow, low, medium, rapid, and high. Overall, the land pressure in the YRDR from 1995 to 2020 reveals high land pressure that SH is the region's center, followed by XZ in northern Anhui, NJ, CA, WX, and SU in southern Jiangsu, HZ, JX, NB, and WZ in Zhejiang, and low land pressure throughout the remainder of the region. Grid level statistics from 1995 to 2020 show that from low to high five levels, the number of land pressure grids in the YRDR declined by 17.06%, rose by 17.88%, reduced by 34.77%, grew by 12.24%, and increased by 29.47%, respectively (Figure 5).

Figure 5. Spatial distribution pattern of land pressure in the YRDR in 1995, 2000, 2005, 2010, 2015, and 2020

The six years of land pressure are specifically 2015>2020>1995>2010>2005>2000 in declining order in the YRDR (Figure 6). Among the provinces, SH has a substantially higher land pressure score than the others, reaching a mean maximum of 60.24 in 2005, while Anhui has the lowest land pressure score, reaching a mean maximum of 39.40 in 2015. Land pressure scores were greater in Jiangsu before 2000 and higher in Zhejiang after 2000, with Jiangsu and Zhejiang having the highest mean land pressure scores in 2015, at 43.65 and 46.07, respectively (Figure S3).

Figure 6. Land pressure scores in the Yangtze River Delta in 1995, 2000, 2005, 2010, 2015, and 2020

3.3 Land pressure trade-off/synergy characteristics

By using a mechanical equilibrium model, we computed the polar angle and examined the predominant traits

of the production pressure, living pressure, and ecology pressure in the quadrant where the polar angle is located. Calculating the combined force F using Equation 10–12 yields the trade-off/synergy of production, living, and ecology pressure, which is then classified into high coordination, basic coordination, out of coordination, and over-out of coordination. The synergy includes high coordination and basic coordination, while the trade-off includes out of coordination, and over out of coordination.

Production pressure, which is greater than both living pressure and ecology pressure, predominates in Quadrant III. The cities of SH, AQ, CI, HS, WZ, and TZ made up the majority of the 5.29% of the YRDR that was situated in quadrant III in 1995. SH dominated the areas with the highest production pressure between 2000 and 2005. As production pressure decreases and living pressure increases in the YRDR from 2000 to 2020, the proportion of production pressure patches in quadrant III falls to 0%, with living pressure dominating the whole region.

The impact of living pressure is greater than the impact of production pressure and ecology pressure in the areas of quadrants IV and V. Quadrant IV represents locations with high living pressure but low ecology pressure, indicating positive living pressure and negative ecology pressure. In general, regions with high living pressure but relatively low production pressure are covered by Quadrant V, which implies positive living pressure and negative production pressure. Quadrant IV contained 86.43% of the YRDR's land area, while quadrant V contained 8.27% in 1995. Quadrant IV held 66.46% of the land area in the YRDR, while quadrant V held 33.54%. This is due to the steady transition of areas in quadrant IV to quadrant V between 2000 and 2020 as a result of regional production pressure becoming progressively less significant than ecology pressure (Figure 7). Living pressure generally predominates in the YRDR, with the dominance fluctuating from 94.71% to 100%. The YRDR does not have an ecology pressure-dominated area, primarily because the local economy has developed and the living pressure is considerably more than the production pressure and the ecology pressure combined.

Figure 7. Spatial pattern analysis of production, living and ecology pressure deviation results and coordination in the YRDR in 1995, 2000, 2005, 2010, 2015, and 2020

Geographically, the high coordinated and basic coordinated areas where production pressure, living pressure, and ecology pressure are most closely synchronized with one another are primarily found in northeastern Jiangsu Province and northern Anhui Province. Most of Zhejiang Province, southern Jiangsu Province, and southern Anhui Province are related to the out of coordination and over out of coordination (Figure 7). The influence of living pressures in the region is significantly greater than the impact of production and ecology pressures, and there is a dissonance in which living pressures are stronger than production and ecology pressures. This is mostly due to natural and socioeconomic factors. In general, from 1995 to 2020, the incoherence between production, living, and ecology pressure in the YRDR is progressively increasing. There is a transition from high coordination, basic coordination, and out of coordination to over out of coordination, but in particular regions, including LYG, SQ, HA, HN, WH, and MAS, there is also a transition from out of coordination and over out of coordination to high and basic coordination. Quantitatively, from 1995 to 2020, there was a decline in coordination, as indicated by the mean and standard deviation of coordination. The proportion of trade-off areas grew from 29.66% to 50.27%, whereas the proportion of synergistic regions declined from 70.34% to 49.73% (Table S3). There is a critical need to coordinate production, living, and ecology pressure, and a pressing need for pressure adjustment and alleviation in the YRDR.

3.4 Model validation of land pressure

We used a Monte Carlo simulation to confirm the uncertainty of the model. Based on a Monte Carlo simulation, Figure 8 depicts the distribution of land pressure fraction values for a grid in 2020. It shows that there is a 4.65 difference between the land pressure score in the 5% quantile and the land pressure score in the 95% quantile. In 2020, this pixel's real land pressure fraction will be 47.10, a difference of 9.87% from the real land pressure score, which is a very minor amount.

Figure 8. The distribution of land pressure scores in the YRDR for a grid in 2020 based on the simulation weight calculation of the Monte Carlo method

Figure 9 displays the land pressure scores for the whole research region and the scores within the 5% and 95% confidence intervals, as well as the ratio of the land pressure scores to the scores from the original assessment at the 90% confidence level. The range of values between the 5% and 95% quartiles for the entire region is between 2.53 and 6.11, and the percent difference is substantially less than the range between 8.74% and 11.95% of the real land pressure evaluation score. Figures 9a and 9b show that the 5% and 95% quintile values are spatially similar and significantly different, with the Southeast scores being significantly higher than the Northwest scores. As a result, the Monte Carlo uncertainty test validates the model evaluation and strengthens the veracity of the model results.

Figure 9. Spatial distribution of uncertainty in land pressure fractions based on Monte Carlo simulation (a) Land pressure score confidence interval 5% quantile fraction (b) Land pressure score confidence interval 95% quantile fraction (c) Difference between the values in the 5% and 95% quantile of the land pressure score confidence interval (d) Ratio of variables to the original evaluation score at 90% confidence level

Discussion

4.1 Evaluation of Land pressure method

In terms of research methodology, this study integrated the three aspects of production, living, and ecology land pressures covering food production pressure, economic development pressure (Zhu and He, 2010), and arable land pressure (Chen et al., 2019) considered by previous research scholars. In comparison to previous fuzzy evaluation studies (Wen et al., 2021; Lu et al., 2022), this study avoided the shortcomings of subjectivity and arbitrariness inherent in the traditional expert scoring scheme by calculating the evaluation scores of each raster cell using fuzzy mathematical methods and fuzzy rules that are more objective and easy to extend, and finally obtaining the land pressure score through weighted summation. Model validation is necessary to clarify the reliability and validity of the assessment outcomes, but only a few research have conducted it. Our model was assessed in this study using the Monte Carlo model, and the findings revealed that the reliability and validity of the evaluation results of this study were excellent.

4.2 Spatial and temporal distribution of land pressure

Our study provides more reliable information for the measurement of land pressure in the YRDR. The geography of the YRDR's land pressure distribution features and temporal evolution pattern were highlighted.

We noted that the pattern of land pressure in the YRDR is "high in the east and low in the west, high in the south and low in the north" consistent with Hu's findings (Hu et al., 2020), and the high-pressure zones of land pressure are grouped (Cheng et al., 2022). While land pressure in NT exhibits a continual diminishing trend, which is consistent with Wang's findings, it is substantially higher in SH, NB, and HZ than it is in other locations (Wang et al., 2020). We discovered that land pressure in LYG and YC exhibits a consistent declining pattern between 1995 and 2010, followed by a growing trend, which supports Wang's findings (Hu et al., 2020). Additionally, we observed that although the rest of the cities had a constant or changing pattern of growing pressure, CA, FY, TA, YZ, ZJ, TL, LA, and AQ displayed a continual declining trend in land pressure. Moreover, we revealed considerable variations in land pressure between economic zones, with Ningbo, Hangzhou, and Suxichang economic zones usually experiencing higher levels of land pressure as a result of greater demographic and socioeconomic pressures (Li and Lang, 2010; Liu et al., 2020). Due to higher living and production demands, urban regions experience higher levels of land pressure than rural ones (Liu et al., 2017). There is a clear relationship between regional development and ecology pressure status, with SH experiencing the highest ecology pressure and SX, NB, and JH experiencing the lowest levels by 2015 which is consistent with Zhang's findings (Zhang et al., 2022). The ecology pressure on the YRDR is also typically rising (Lin et al., 2020; Zhang et al., 2022). Therefore, to reduce land pressure, population and industrial growth should be reasonably controlled, pressure should be gradually transferred to low-pressure areas, the level of response should be improved while reducing high pressure, the ratio of population resources in the YRDR should be adjusted, and a reasonable spatial optimization and control policy should be developed.

4.3 Land pressure trade-off/synergy relationship

To achieve a balance between production, living, and ecology pressure in the YRDR, it is important to investigate the trade-off/synergy relationship of land pressure in that region. This research also offers new ideas for measuring the degree to which production, living, and ecology pressure are coupled in the YRDR. The YRDR has a significant regional heterogeneity in the land pressure trade-off/synergy relationship, which alternates throughout time (Lin et al., 2020). Except for SH, places with high production and living demands and low ecology pressures are mostly where regions with high levels of conflict (strong trade-offs) are located. This is in agreement with Zhang’s results (Zhang et al., 2019). In agreement with the findings of Chen’s study, the YRDR’s production-living-ecology pressure synergy rapidly worsened. The degree of synergy fell from 70.35% in 1995 to 49.74% in 2020 (Chen and Zhu, 2022). The YRDR’s production-living-ecology pressure progressively shifts from synergistic development to trade-off development and represents various trade-offs under the influence of economic and social growth as well as regional variances (Huang et al., 2017). Production, living, and ecology pressures are now traded off at a high stage, with production and living pressures being higher than ecology pressures. This does not mean that ecology pressures are lessening, only that they are increasing at a much slower rate than production and living pressures. As urbanization advances, production and living pressures are elevated and living pressures are particularly prominent. The findings of earlier research by academics for the Hengduan Mountains (Shi et al., 2018), the Three Gorges reservoir area (Li et al., 2018), and the eastern and southern high hilly sections of Zhangjiakou (Liu et al., 2018) differ slightly from those presented here. This is primarily due to the mountainous region in the southwest, which has a complex topography and an improved rate of urbanization. The living pressure will be reduced due to the expansion of construction land and the urbanization process, but the YRDR’s high level of urbanization, which is characterized by a stark contrast between human and land, production development, and environmental protection, will exert pressure on the area’s already-saturated living space, increasing living pressure (Li et al., 2019). To promote socioeconomic transformation development and advance coordinated and sustainable development, it is required to modify the interaction between production, living, and ecology in the process in future.

4.4 Innovations and limitations

This study combines objective empowerment and raster cells to create a land pressure evaluation index system based on the production-living-ecology perspective in the YRDR. This study’s results can be used as an exploratory supplement to the current research findings of the evaluation category to deepen the comprehensive understanding of the impact of development on land pressure in the YRDR in the context of regional integration. The chosen quantitative indicators must be further enhanced and augmented, nevertheless, because of regional variations in resource endowments and the abundance of complicated indicators. In the meanwhile, further research has to be done on the fusion of data at various scales and how to increase the precision of rasterizing socioeconomic data. More research is required on the mechanisms underlying land pressure generation and its motivating elements.

Conclusions

This study builds a land pressure evaluation model for the Yangtze River Delta region based on the perspective of production, living, and ecology pressure and the fuzzy comprehensive evaluation method. We evaluated the land pressure in the Yangtze River Delta region and examined the patterns of its regional and temporal evolution in 1995, 2000, 2005, 2010, 2015, and 2020. The trade-off/synergy relationship between production, living, and ecology constraints in the YRDR was examined using a mechanical equilibrium model. The following are the main results and recommendations.

- The land pressure evaluation model constructed from three aspects of production-living-ecology can effectively reflect the level of land pressure in the Yangtze River Delta region. A general pattern of "high in the east and low in the west, high in the south and low in the north" can be seen in the Yangtze River Delta region’s spatial distribution of land pressure, and the six-year range from high to low is as follows: 2015>2020>1995>2010>2005>2000.

- The level of production pressure in the Yangtze River Delta region shows a declining trend, the level of living and ecology pressure shows a rising trend, the spatial distribution of production pressure is consistent with the spatial distribution of land pressure, the level of living pressure shows a trend of high in the southeast and provincial capital cities - lower in the northwest and the ecology pressure changes from high ecology pressure in the northwest and low ecology pressure in the southeast.
- The Yangtze River Delta region's incoherence between production, living, and ecology pressure progressively got worse during 1995 - 2020, mostly in the form of high coordination, basic coordination, and out of coordination into out of coordination.

Provide a reference for the spatial distribution characteristics of land pressure in the Yangtze River Delta region, which helps reduce land disputes, enhances the region's sustainable development, and serves as a useful guide for research in other cities.

Declaration of competing interest

The authors declare no known competing financial interests or personal relationships that could have influenced this paper.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (Grant No. 42001212), the Graduate Innovation Program of China University of Mining and Technology(2022WLKXJ093)and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX22_2474).

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