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Identification of Land Use Function Bundles and Their Spatiotemporal Trade-Offs/Synergies: A Case Study in Jiangsu Coast, China

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Abstract: Land use multifunctionality (LUMF) is a pragmatic means of resolving land use conflicts and realising regional sustainability and has critical importance in land system science. In this study, we constructed LUMF classifications from a sustainable perspective and quantified and analysed the deliveries of land use functions (LUFs) in the coastal area of Jiangsu Province, China. On this basis, the "bundle" concept was innovatively introduced into the LUMF research framework to analyse the spatiotemporal effects of trade-offs and synergies among multiple LUFs. The results showed that high-value LUF geographic units tended to cluster in human-dominated landscapes. During the study period (2000–2018), the average provision of regional multifunction increased slightly, while the subfunctions changed in different trends. Four LUF bundles (agricultural zone, mosaic cropland–rural housing zone, coastal natural and seminatural landscape zone, urban development zone) were identified, each having different dominant LUFs and landscape configurations. In each LUF bundle, the most common trade-offs were observed in the environmental and economic functions. The space incompatibilities caused by land development demand in different subregions created a trade-off and synergy among multiple functions. Moreover, LUF relations were not static over time, owing to the effects of urbanisation, coastal reclamation activities, and agriculture protection policies. Based on the above results, this research proposes land use optimisations for different multifunctional areas.

Keywords: land use functionality; LUF bundle; LUF relationships; spatiotemporal effects; coastal zone

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1. Introduction

Land change significantly impacts biodiversity, biogeochemistry processes, and climate change; such change often results from multiple human demands on the land [1,2]. In the past, Earth observation from the land use and land cover perspectives was the main method of characterising land changes [3]. Generally, each land use has multifunctionality, which can provide a wide range of goods and services and result in both intended and unintended outcomes [4]. These characteristics of land use multifunctionality (LUMF) cannot be obtained from Earth observations. For example, agricultural land can not only provide grain production but also social-ecological functions such as agricultural work opportunities, agricultural landscape aesthetics, and biodiversity. LUMF enables a more comprehensive assessment of land changes and aims to support efforts to identify solutions for land-use conflicts, manage the complexity of interactions between different land uses, and regulate the relationship between humans and the environment [5–7]. Thus, an accurate understanding of land use multifunctionality and the interactions between the functions are essential for steering land changes toward sustainability.

Our research selected the coastal area of Jiangsu Province in eastern China as a case area; this region belongs to an important maritime transportation hub and is of great significance to the marine economy in China. Moreover, the region has a large national nature reserve and farmland areas owing to abundant wetlands and agricultural resources. With rapid urbanisation and population growth, the demand for urban space is increasing [8]. In recent decades, Jiangsu Province has implemented a series of ambitious coastal development strategies which have accelerated the process of tidal flat reclamation in the region, providing important backup resources for urban construction and agricultural development [9]. Newly reclaimed land is actually allocated according to the ratio of agricultural land, built land, and natural land, in proportions such as 2:6:2 or even 2:7:1 [10]. It has also been widely reported that high-intensity reclamation activities have caused deterioration in the wetland ecological environment, reductions in species diversity, and declines in resource and environmental carrying capacity [8,11,12]. In an effort to protect and restore the coastline and enhance the ecological function of wetlands, the Jiangsu government has sought to curb the trend of wetland reduction since 2016. With the transformation in the coastal development strategy, the contradiction of land use in this area has become increasingly prominent. Therefore, it is necessary to analyse the influence of historical policies and social changes through the dynamic changes and interactions of multiple LUFs, which can reveal feasible paths for alleviating land space utilisation conflicts and promoting sustainable integrated coastal management.

2. Literature Review

2.1. LUMF Framework and Quantification

Sustainable development theory plays a central role in the formation and evolution of the LUF research framework [13]. Based on sustainable development theory, an innovative conceptual LUMF framework that included three basic functions: economy, society, and environment, was established. This framework was first used to estimate how policy implementations differentially impacted sustainability in 27 European countries. Hereafter, in China, this framework was applied to support the government in formulating sustainable land-use policies [14,15]. Previous work primarily focused on establishing the LUMF-evaluated index on an administrative scale because of the lack of object-based indicators and excessive reliance on socioeconomic data [6]. In recent years, LUMF has been comprehensively quantified using multiscore and multiscale data and mapped on a fine scale; on this basis, we can analyse its historical dynamics to measure the continuous delivery capability of the region. Quantifying LUMF is challenging because of its ambitious conceptual scope and diverse classification system. Because the comprehensive framework for LUMF assessment remains partial and incomplete, numerous researchers continue to develop new frameworks for special research questions. For example, Liu et al. (2018) [4] quantitatively identified and evaluated LUMF from the perspective of structure, function, and well-being to propose a differentiated land use zone in Zhangjiakou City. Zhang et al. (2019) [5] proposed a conceptual index system from the perspective of the interrelationship and influence among economy, society, and ecology. In addition, Zhou et al. (2017) [6] and Fan et al. (2018) [8] presented production, living, and ecology functions based on the "National Land Planning Outline (2016–2030)" in China, which greatly promoted the richness of the LUMF comprehensive assessment framework.

2.2. LUF and Land Use Zoning

The concept of land use multifunctionality has become an important tool for land use zoning. Since 2000, the Chinese government has continuously emphasised the importance of coordinating land space, people, resources, and environments in land planning at all levels and proposed optimising land space development patterns based on the main function (as specified in National Main Functional Area Planning (2010)). Chinese scholars have constructed a classification and evaluation system of "production-life-ecology" spaces based on the dialectical relationships between land use functions (LUFs) and land use types [16,17]. The spatial patterns of LUMF and their interactions are important factors in managing and optimising the development and utilisation of land space. Accordingly, a series of comprehensive land-use function zoning schemes based on temporal and spatial LUMF dynamics and their relationships have been proposed to support sustainable land use management [4,5,18].

2.3. Bundle

"Bundle" is defined as a group of ecosystem services that repeatedly appear together across space or time, thus forming geographical aggregates with high delivery for a specific set of services [19,20]. Identifying the spatial patterns and change trajectories of the spatial bundle are also often employed to analyse the dynamics of the supply and interaction of functions/services over time and the influence of socioeconomic conditions [21–25]. At present, some LUMF studies have adopted the cluster method of identifying bundles when conducting land use functional zoning. Including Zhang et al. (2019) [26] clustered functional significance grades to acquire an integrated multifunctional zoning scheme using the K-means clustering method. Fan et al. (2018) [8] included all subfunctions calculated in 2000 and 2015 in a cluster analysis to reveal four distinct zones of multiple functions at the county level and further analysed the difference in LUMF supply levels in each subarea. However, there is almost no research analysing changes in LUMF supply levels and their relationships through LUMF dynamic zoning. Additionally, to formulate targeted policies for multifunctional landscape management and optimisation within subzones, it is necessary to further identify the conflicts and synergies of multiple functions within the bundle to reduce trade-offs, enhance synergies, and realise multifunctional land use [27]. Therefore, integrating the "bundle" concept into the LUMF research framework and analysing the spatial transfer of LUF bundles and their internal functional interactions from a historical perspective helps elucidate how LUF relationships change over time and space and better understand their response to socioeconomic conditions and policies. Such analyses are imperative in supporting sustainable land management in multifunctional areas.

In this research, we used multiscore, multiscale data and geographic modelling tools to construct a LUMF classification framework based on the dimensions of sustainable development and quantified the delivery of 11 LUFs across the Jiangsu coast from 2000 to 2018. We then integrated the "bundle" concept into the LUMF framework and extended it to spatial–temporal analysis. Specifically, this study aimed to (1) quantify and analyse coastal LUMF from a sustainable perspective; (2) identify different types of LUF bundles and examine their dynamics; (3) determine the multiple LUF relationships within each bundle and their changes over time; (4) combine the dynamic trajectory of LUF bundles and trade-offs and synergies among LUFs to analyse the impact of social and economic activities and policies; (5) propose land-use optimisation strategies for different multifunctional areas.

3. Materials and Methods

3.1. Study Area

The study area (Jiangsu coast) is located in the coastal area of Jiangsu Province, China (31°40′52″–35°7′39″ N, 118°24′6″–121°57′28″ E). This area, in which three economically significant regions (The China Coastal Economic Zone, Yangtze River Economic Zone, and Longhai-Lanxin Traffic Line) intersect, has unique geographical advantages. The Jiangsu coast is composed of 18 counties with a total area of 3.36×10^4 km^2 and a coastline of 954 km (Figure 1). The total area of tidal flats on the Jiangsu coast is approximately 5002 km^2, which accounts for 25% of the tidal flats in China. It is noteworthy that the tidal flats are expanding seaward at a rate of 14 km^2/a [28]. The reclaimed tidal flats, comprising an area of up to 3350 km^2 during 1950–2015, mainly support agriculture, aquaculture, and industry [11,28]. The 17 ports along the Jiangsu coast support the development of coastal industries and shipping. As of 2019, the total population of the Jiangsu coast was

19.03 million; its GDP per person has reached 9.57 × 10^4 RMB/person, which is higher than the national average level (7.09 × 10^4 RMB/person) ("Jiangsu Statistical Yearbook"). With its unique geographical conditions and abundant tidal flats, Jiangsu Coast plays an important role in national economic development, and the "Development Plan for Jiangsu Coast" was initiated in 2009. However, this area faces great challenges stemming from the trade-off between the land demands of rapid urban growth and the protection of cropland and ecological systems [11,29].

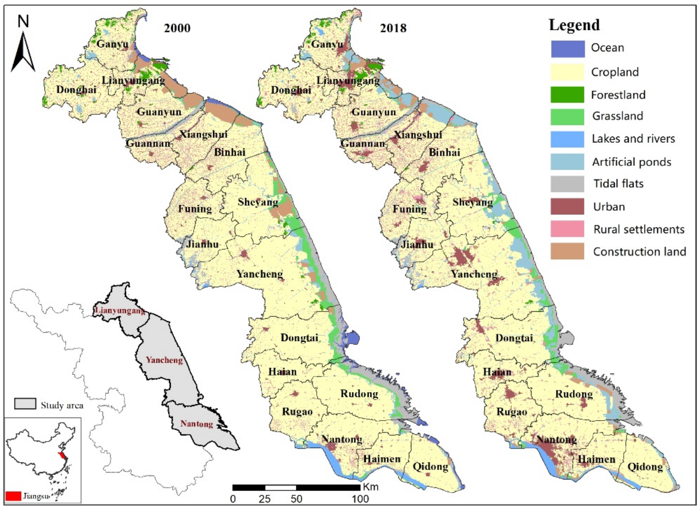

Figure 1. Location of the study area in Jiangsu coastal zone and the land-use category conversion from 2000 to 2018.

3.2. *Quantification of LUMF*

The LUMF classification of social, economic, and environmental factors illustrated the linkage between multifunctional land use and sustainable development, with the objective of supporting decision making for sustainable use of regional land [5,13,14]. In this study, eleven LUFs involving the dimensions of society, economy, and environment were chosen by considering the benefits of land use in social security, human survival and development, and natural environmental regulation (Figure 2). Specifically, social function ensures social development and maximises human well-being and includes the provision of work (PW), recreation (RE), and culture (CU). PW is a premise for maintaining social stability and involves the direct utilisation of agricultural resources to support employment. RE is the regional potential for entertaining people, as expressed by the influence of local natural and recreational attractions. CU represents the benefits provided by landscape aesthetics associated with local culture. The economic function provides living materials, carrying space, and infrastructure for human survival and economic development and is subdivided into food production (FP), economic support (ES), residential carrier (RC), and transport (TR). FP is the main land product of agricultural activities and satisfies the basic physiological needs of the human body. ES represents the benefits of nonagricultural activities in promoting economic development. RC and TR refer to living and transportation spaces that offer a convenient environment for human survival. Environmental functions provide suitable environmental conditions for human survival and socioeconomic development and mainly include the functions for maintaining and regulating the ecosystem, e.g., water regulation (WR), biodiversity conservation (BC), climate regulation (CR), and soil conservation (SC). WR is the water production capacity of different land-use systems to regulate runoff. BC provides habitats to adapt to the survival and developmental conditions of individuals and communities. CR represents the ability to control greenhouse gas emissions through carbon sequestration. SC is the ability to reduce soil erosion and conserve soil nutrients by means of covered vegetation. In general, these functions represent the most relevant economic, environmental, and societal aspects of a region. Table 1 lists the description, indicators, and quantification methods for these 11 functions. Each indicator was assigned to a 1 km × 1 km grid through geographic models and related spatial technologies; this facilitated a comprehensive evaluation of LUMF on a microscale (quantification methods are detailed in the Supplementary Material).

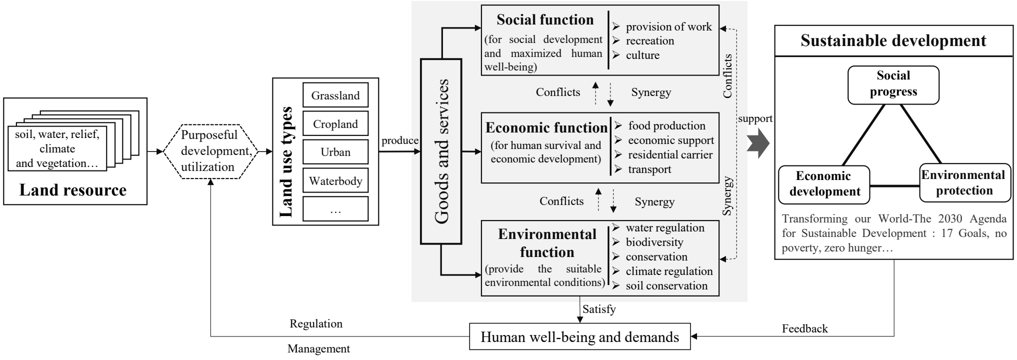

Figure 2. Classification framework of LUMF from the perspective of sustainable development.

Table 1. Indicators and methods for quantifying LUFs.

Dimensions	Functions	Indicators	Unit	Quantification Method
Society	Provision of work	agricultural employee	Person	The agricultural employees in each county were allocated to cropland grids, and their spatial distribution was corrected using NPP data.
	Recreation	Recreation Potential	Index (Dimensionless)	The comprehensive influence score of the attractions for each grid was quantified according to the distance to the attractions and the benefits of the attractions.
	Culture	landscape aesthetics values	Comparable price	Evaluation method of the value equivalent factor in a unit area.
Economy	Residential carrier	Residential population	Person	The total population of each county was allocated to the residential units according to nighttime light intensity variation.
	Economic support	Nonagricultural economic output	Comparable price	The nonagricultural economic output values of each county were allocated to the build up land units according to nighttime light intensity variation.
	Food production	Food calorie output	kcal	The grain yield of each grid was multiplied by the corresponding food nutrient composition coefficient.
	Transport	Regional accessibility	min	The cumulative time cost of arriving at the nearest regional centre.
Environment	Water regulation	Water Yield	mm	Water Yield model in Integrated Valuation of Ecosystem Services and Tradeoffs software (InVEST).
	Biodiversity conservation	Habitat quality	Index (Dimensionless)	Habitat Quality model in InVEST.
	Climate regulation	Carbon sequestration	$gc/m^2/a$	$CR = 1.63 \times NPP$
	Soil conservation	Sediment retention	kg/km^2	Sediment Delivery Ratio model in InVEST.

3.3. Analysis

3.3.1. Pattern and Spatiotemporal Changes in LUFs

Because of the incomparability caused by the inconsistent units of indicators in different dimensions, all LUFs were standardised to a range of 1 (low)–5 (high) by quantile division [30]. The priorities of all quantified LUFs were equal in this study; therefore, each had an equal weight (1/11). The land use multifunctional index was calculated as the sum of the products of standardised LUF indicators and weight in order to determine the ability of each grid to provide multiple functions simultaneously. Each LUF was mapped in ArcGIS 10.5 (2019), and its spatial clustering was quantified using Moran's I. The changes in LUFs were calculated according to the differences between the LUF values observed at the end and beginning of the study.

3.3.2. LUF Bundles

Based on the concept of an ecosystem service bundle, our research defined a land-use function bundle (LUFB) as a group of consistent related LUFs that appeared repeatedly in time and space [20,31]. Each LUFB was composed of a considerable number of grid cells, where the similarities between LUF values and evolution trends were greater within the LUFB than among different LUFBs [24]. A K-means cluster analysis of an entire time series was used to divide the clusters into land-use function data [23]. Specifically, the LUFBs based on LUF spatiotemporal characteristics were analysed and identified using the K-means cluster analysis tool in Python (for detailed calculation principles, please refer to Gao et al. (2019) [32] and Kanungo et al. (2002) [33]). The LUFBs for each year were mapped using ArcGIS 10.5 to visualise their spatial distribution dynamics over time. We calculated the area transfer matrix of each LUFB from 2000 to 2018 to analyse the main evolution trajectories over time and visualised it through a histogram. The diversity of the set of LUFs provided in each bundle represents the adequate number of LUFs it can provide, which facilitates comparisons of functional richness between LUFBs [22,23]. In this study, the diversity results were drawn using a Nightingale Rose diagram. The formula for calculating bundled diversity is as follows [23]:

$$H = 1/((1 - SI)) \tag{1}$$

$$SI = 1 - \sum_{i=1}^{11} (\frac{V_{LUF_i}}{S_{V_{LUF}}})^2 \tag{2}$$

where H represents the adequate number of LUFs contained in the LUFB, SI is the Simpson's diversity index of LUFB, V_{LUF_i} represents the average value of the i-type LUF in the LUFB, and $S_{V_{LUF}}$ represents the sum of the average values of all LUFs in the LUFB.

3.3.3. Identification and Analysis of LUF Interactions

Factor analysis with varimax rotation was developed to detect internal interactions within each LUFB; this was performed after passing the KMO and Bartlett sphere inspection tests [27,34]. This method not only identified a set of related LUFs but also provided important information such as types of interactions (trade-offs/synergies) and spatial intensity [34]. Specifically, the LUF values of each grid contained in the LUFBs for each study year were extracted and imported into SPSS v25 for factor analysis. Then, the number of factors (LUF groups) to extract in each LUFB was determined by the screen plot and the cumulative factor variance [34]. The factor scores of each grid were mapped in ArcGIS 10.5 to visualise the spatial heterogeneity of LUF relationships [27]. Meanwhile, the multiple LUFs (or LUF changes) involved in each factor of LUFBs covaried along with the corresponding factor scores, which were visualised based on the generalised additive model (GAM) [27]. GAM is a nonparametric method that can smoothly fit a nonlinear curve based on data without reliance on a mathematical model [35].

In this study, GAM curves and Nightingale Rose plots were all performed using ggplot2 in the R statistical software package (version 4.0.2, 2020) (https://www.r-project.org/).

4. Results

4.1. Spatial Variations and Dynamic of Individual LUFs

The LUF quantification results revealed great spatial heterogeneity and complicated dynamics occurring in multifunctional patterns across the Jiangsu coastal area. All LUFs, except for RC, were spatially aggregated on the landscape rather than randomly distributed (Figure 3; Supplementary Materials Figure S1). In general, human-dominated landscapes (e.g., built up areas and cropland) were inland areas with relatively higher multifunctionality, while offshore wetlands gathered a considerable number of low multifunctionality grids. The distribution of individual LUF clusters was closely related to local social, economic, and geographical environmental factors. For example, coastal tidal flats and wetlands provided CU and BC, CR was localized in the lush vegetation landscape, and RC and ES were found in built up land and gradually decreased as they extended to the periphery. PW and FP were mainly clumped in flat and water-dense areas and varied greatly among different towns, perhaps as a result of agricultural input and cultivation.

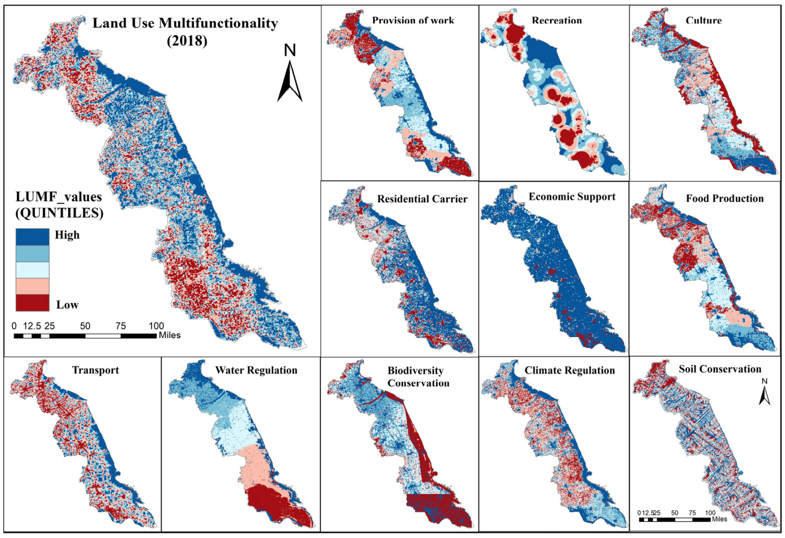

Figure 3. Distribution of 11 LUFs in 2018 by quintiles. Moran's I index values were calculated in 2000, 2010, and 2018 and showed that the spatial distributions of all LUF indexes were significantly clustered ($p < 0.01$ in all study years), with the exception of RC ($p2000 < 0.01$, $p2010 = 0.025$, $p2018 = 0.104473$).

Trend analysis on the grid level indicated that the changes in LUF patterns differed in terms of the extent and positions of improvement or degradation (Supplementary Materials Table S1, Figure S2). From 2000 to 2018, the values of the improved and degraded LUMF pixels changed by 0.35 and −0.30 on average, respectively; the area ratio of the above two-pixel types was 1.57, which revealed a rising multifunctional trend across the Jiangsu coastal region. Regional multifunctional supply showed observable spatial variation, which presented as a decline in the southern agglomeration and a general increase in the central and northern regions (Supplementary Materials Figure S2). There were more substantial changes in subfunction patterns, in which the provisions of ES, RC, RE, and TR increased, and the provisions of PW decreased overall based on the statistics of the improved and degraded pixels. The areas where the above subfunctions (except RE and PW) changed over time largely occurred around human-dominated landscapes (Supplementary Materials Figure S2). In addition, the delivery of FP, PW, CU, and CR was found to drop steeply in the southern Jiangsu coast, while the BC supply dramatically increased in this area. Meanwhile, a pronounced decline in WR and SC appeared in the mixed mosaic of northern cropland and rural residential areas.

4.2. Changes in Patterns of LUF Bundles across Landscapes over Time

Based on the types and values of eleven LUFs provided over time, cluster analysis divided the Jiangsu coastal area into four clusters in the landscape: a specialised agricultural zone (LUFB1), a mosaic cropland–rural housing zone (LUFB2), a coastal natural and seminatural landscape zone (LUFB3), and an urban development zone (LUFB4) (Figure 4). Four LUFBs were clustered geographically within the years 2000, 2010, and 2018 (Figure 4a, Moran's I, $p < 0.001$). LUFB1 and LUFB2 were the dominant bundles, accounting for ~35% and ~31% of the study area, respectively (Table 2). They occupied large contiguous areas to the north and south, respectively. From 2000 to 2018, the area of LUFB1 did not fluctuate much over time and tended to be more clustered in space. The area of LUFB2 increased by 2.34% and spatially spread in the coastal direction. LUFB3 was mainly distributed in the coastal zone, while LUFB4 was scattered throughout the study area. During the study period, the bundles with the greatest net change were LUFB4 with a 4.18% increase and LUFB3 with a 6.55% decrease. Evidently, the range of LUFB4 expanded outward from the original, while LUFB3 shrunk significantly.

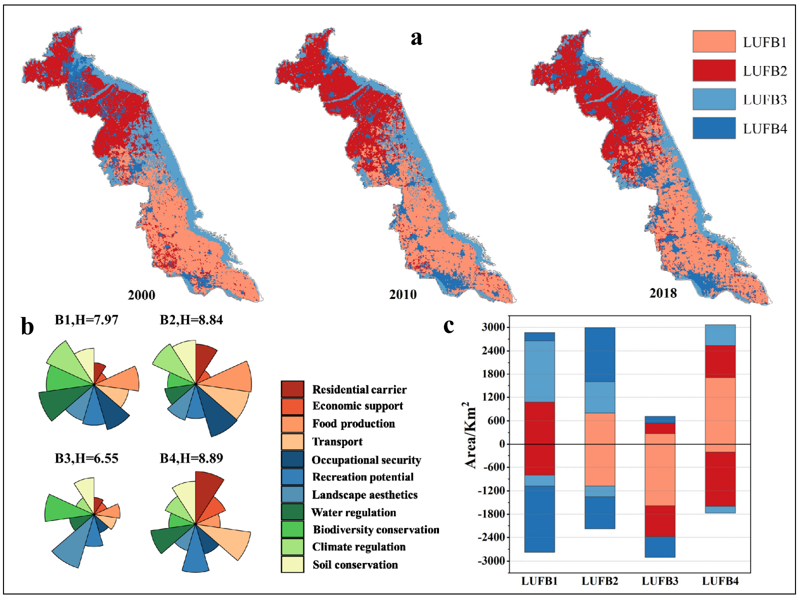

Figure 4. The mutual transfers among LUF bundles over time (**a**,**c**) and the diversity in each bundle (**b**). (**a**) The map shows spatial distributions of bundled LUFs over time; (**b**) The Nightingale Rose diagram shows the number of effective LUFs provided by each of the four bundles and their advantageous functions; (**c**) The histogram reveals the main trajectories of changes that provide the source and transfer of each bundle from 2000 to 2018. The positive values represent the area where the other three LUFBs transform into this LUFB, while the negative values represent the area where this LUFBs transform into the other three LUFB.

Table 2. The LUF bundles area proportions: 2000, 2010 and 2018.

Bundles	Area Proportion/%			Net Change
	2000	2010	2018	
LUFB1	35.13	35.57	35.16	0.03
LUFB2	30.16	31.89	32.50	2.34
LUFB3	23.37	19.88	16.83	−6.55
LUFB4	11.33	12.67	15.52	4.18

The order of the diversity of the four LUFBs was as follows: LUFB4 (H = 8.89) > LUFB2 (H = 8.84) > LUFB1 (H = 7.97) > LUFB3 (H = 6.55), indicating that the effective number of LUFs provided by each bundle was different (Figure 5b; Supplementary Materials Table S2).

Clearly, the bundles covered by different landscapes specialised in a distinct set of LUFs (Table 3). Specifically, the urban, rural settlement, and industrial land areas in the bundle with the highest diversity value (LUFB4), respectively, account for more than 80%, 20%, and 20% of the urban, rural settlement, and industrial land areas in the entire study area; therefore, urban and industrial development dominated land exploitation in this area, resulting in the high provision of RC, ES, TR, and CU (Figure 5b). Large forest areas (~65%), grasslands (~87%), water areas (~60%), and wetlands (~90%) gathered in LUFB3, which continued to produce ecological and social functions (i.e., CU, BC, SC, and RE). LUFB1 and LUFB2 both specialise in functions of FP, PW, and CR, owing to a wide stretch of cropland. However, LUFB2 was also dotted with a large number of rural settlements across cropland, which produced some peculiar functions such as TR and RC.

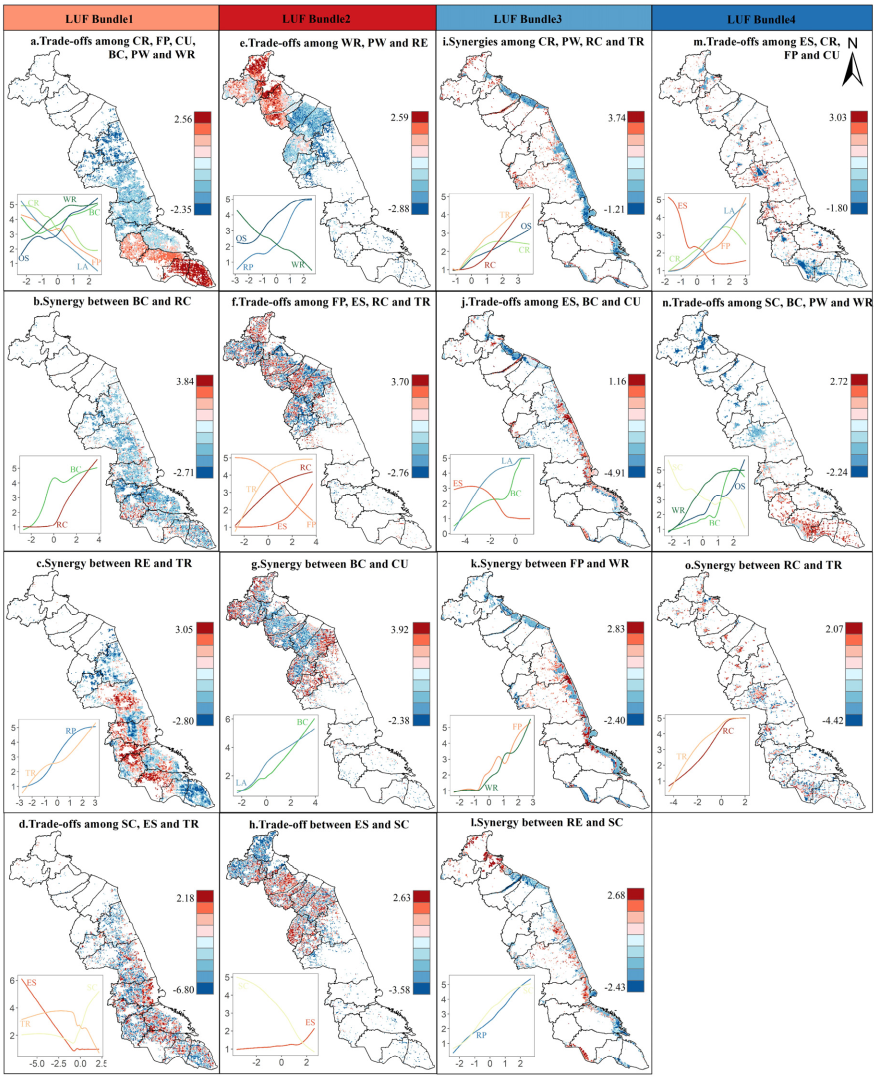

Figure 5. Spatial variations in factor scores of trade-offs and synergies among multiple provided functions in four bundles (2018). The subgraphs are specific combinations of trade-offs and synergies that belong to different LUFBs (LUFB1: **a**–**d**; LUFB2: **e**–**h**; LUFB3: **i**–**l**; LUFB4: **m**–**o**). The inset shows the responses of the LUF value (ordinate) to the factor score (abscissa), and the nonlinear curves between them are fitted by GAM. As for the trade-offs among bundled functions, blue areas indicate high values in positive factors and low values in negative factors, while red areas indicate low values in positive factors and high values in negative factors. Regarding the synergies among bundled functions, blue areas indicate that the values of all factors are high, while red areas indicate that all these functions have low values.

Table 3. Percent of land use structure (% of total) for each bundle: 2000, 2010, and 2018.

Year	2000				2010				2018			
LUFB	**LUFB1**	**LUFB2**	**LUFB3**	**LUFB4**	**LUFB1**	**LUFB2**	**LUFB3**	**LUFB4**	**LUFB1**	**LUFB2**	**LUFB3**	**LUFB4**
ocean	3.86	0.00	94.69	1.45	7.02	0.00	85.96	7.02	0.00	0.00	0.00	0.00
cropland	43.53	33.58	12.85	10.04	45.69	35.12	9.82	9.37	45.78	36.71	6.39	11.12
forestland	5.17	5.78	72.95	16.11	6.69	18.79	61.78	12.74	5.99	16.90	59.86	17.25
grassland	5.06	3.77	90.47	0.70	2.71	5.27	89.61	2.41	5.61	7.74	82.85	3.79
lakes and rivers	18.09	12.06	63.23	6.61	11.65	15.46	62.25	10.64	15.00	16.35	54.04	14.62
artificial ponds for fishing and other domestic purposes	11.56	11.88	70.47	6.10	8.65	10.66	76.42	4.28	5.96	5.91	83.64	4.49
muddy tidal flats and wetland	3.54	2.06	92.34	2.06	2.34	3.75	92.12	1.80	3.95	4.83	87.60	3.62
urban	8.84	12.79	2.33	76.05	4.34	11.64	1.39	82.62	2.46	7.04	0.84	89.66
rural settlements	13.33	53.67	7.58	25.42	12.92	62.47	4.16	20.46	12.54	56.93	4.85	25.67
construction land mainly for mining and transportation	0.51	2.03	84.75	12.71	2.13	5.67	68.26	23.94	7.37	5.22	54.69	32.72

Figure 5 In terms of spatial dynamics, the mutual transfers among LUFBs primarily formed six trajectories of changes, including the transfers from LUFB1 to LUFB2 and LUFB4, the transfers from LUFB2 to LUFB1 and LUFB4, the transfer from LUFB3 to LUFB1, and the transfer from LUFB4 to LUFB2 (Figure 5c). Among them, the evolution from LUFB1 to LUFB2 and LUFB4 represented urban expansion that encroached on adjacent cropland, where the high provision of FP eventually resulted in high ES values. The area that experienced the transfer from LUFB3 to LUFB1 clustered in coastal tidal flats, where the changing trends of BC, CU, FP, and PW conflicted over time, indicating that reclamation of tidal flats into cropland created great pressure on the ecological environment. Approximately 11% of LUFB2 was transformed into LUFB1 because of the overall improvement of ecological functions and degradation of RC and TR over time, reflecting the effect of ecological restoration after land consolidation efforts (i.e., reclaiming abandoned residential areas into farmland).

4.3. Trade-Offs and Synergies among Bundled LUFs

Figure 5 and Supplementary Materials Figure S3 show the spatial changes in the types and intensity for trade-offs and synergies in each LUFB and response changes in corresponding LUFs and factor scores over time; these reveal the dynamics, spatial heterogeneity, and nonlinearity of multiple LUFs. Each spatial bundle presents different numbers and types of LUF interaction combinations. In LUFB1, four sets of LUF interactions were identified in each studied year; these interactions were mainly manifested in antagonistic relationships among environmental functions (BC, SC, and WR) and socioeconomic functions (FP, ES, TR, RE, and CU). In LUFB2, 13 sets of LUF relationships were detected, and these relationships varied each year. The most common trade-offs appeared between economic functions and FP and between economic functions and social-environmental functions. All identified LUF relationships were positive in LUFB3, except for the trade-offs among ES, BC, CU, and RE in 2010 and 2018. In LUFB4, ES showed strong negative correlations with FP social-environmental functions.

5. Discussion

5.1. LUF Characteristics of Jiangsu Coastal Area

In the study area, the quantified LUFs exhibited distinct spatial aggregation, as shown by the geographical patterns of the provision of each individual LUF (Figure 3; Supplementary Materials Figure S1). ES, RC, and TR were most prominent in metropolitan areas, owing to their highly developed economy and trade, resulting in population growth and generation of generous employment opportunities, which was consistent with the prevailing perception [5]. PW and FP were consistently distributed in the landscape, indicating that increasing input of agricultural labour generated more agricultural products. High-value PW and FP were mainly concentrated in northern cropland, which could be explained by the differences in intensive agriculture and individual household management among regions (e.g., types of planted crops and grain crop share). Areas with high RE were clumped in urban, peri-urban, and natural landscapes. The densely populated systems provided more recreation functions, including various tourist facilities (e.g., amusement parks, museums, parks). RE from landscapes of forests and wetlands resulted from people having positive experiences with nature [24]. CU and BC were most concentrated in the coastal wetlands, grass, and forests, where low population density imposed high naturalness and low habitat degradation [27]. Southern cropland and built-up areas became ample WR-aggregated zones, which were highly related to local rainfall and evapotranspiration based on the perspective of water balance [36]. The Jiangsu coastal plain is characterised by low-lying flat terrain and dense water networks, where the high runoff potential generated by fragmented river channels increases soil loss; consequently, this region exhibits complex and scattered soil erosion patterns [8]. Furthermore, plantations with dense coverage were found to be able to effectively absorb rainfall through the canopy, surface layer, and root system to reduce soil erosion [27,30], so northern forests had high SC. This study only estimated carbon sequestration by above-ground vegetation without considering soil carbon pool, which explains the high CR values of dense vegetation landscapes.

The grid-scale analysis reported that the trajectories of LUF changes over time were not uniform across the Jiangsu coast (Supplementary Materials Figure S2). The overall improvements in regional ES, RC, RE, and TR were closely related to the increasing housing, economic, and transportation demands resulting from population growth [8]. However, the decrease of OS was primarily due to the reduction of rural labour caused by population migration under urbanisation [37]. Meanwhile, we also found that several aggregations composed of a set of LUFs experienced similar temporal changes; for example, the provision of FP, PW, and CR continued to decline across the southern Jiangsu coast, and WR and SC decreased significantly in the mixed areas of northern cropland and rural resettlements (Supplementary Materials Figure S2). The formations of these aggregations were closely related to the complex change processes of the local social-ecological systems, resulting in the emergence of some complex interaction relationships among LUFs at the spatiotemporal scale.

5.2. LUF Relationships

Although the reconstruction of bundles (clusters) and their trajectories to understand ES dynamics exists at the scale of municipalities or grids in the field of ecology, few studies have identified LUF bundles to support the optimisation of crucial LUF trade-offs, particularly in economically developed coastal areas [23,24]. Therefore, we applied K-means cluster analysis to identify groups of grids with similar sets of LUFs, resulting in four distinct LUFBs with clear boundaries and spatial agglomeration. Interestingly, multifunctional bundles tend to be dominantly specialised in a small set of LUFs, and the numbers and types of these advantageous LUFs remained almost static over time, which could be explained by the relatively stable land use structure within each bundle (Figure 4b; Table 3; Supplementary Materials Table S2). Similar to the results reported by Swedish and Danish studies, the human-dominated bundles (LUFB2 and LUFB4) were found to be clusters with high LUF production [22,24]. The multifunctionality reflected by high diversity values in these social-ecological systems was associated with high delivery of economic and social functions, as ecological functions were often sacrificed to support urban and industrial development [8,37,38]. Although the vast and fertile cropland of LUFB1 and LUFB2 contributed to the high supply of FP and PW, the heterogeneity of the landscape composition showed that these two bundles were different in terms of functions of rural ecology and life, mainly affecting the preservation of the cropland ecosystem health for LUFB1 and the facilitation of rural living and transport for LUFB2. The bundle with the lowest diversity value (LUFB3) was characterised by high delivery of BC, SC, and CU, which are closely related to the high naturalness and low human threats in coastal wetlands.

We provided empirical evidence that LUF interactions on the landscape scale were nonlinear and heterogeneous (Figure 5; Supplementary Materials Figure S3). The strong trade-offs among environmental functions (e.g., BC and CR) and economic functions (e.g., TR and ES) were widely detected across the Jiangsu coast, which was in line with previous assessments in the economically prosperous regions of China [4,5] and Denmark [24]. This shows that the conflict between environmental protection and economic development is worthy of attention in this area. Essentially, the spatial incompatibilities of land use caused by the inconsistent development goals of different social-ecological systems were the roots of the LUF trade-offs [5]. Urban and industrial development determined that the demands for land utilisation mostly involved commerce, housing, transport, and industry, which led to fragmented and isolated agricultural and natural landscapes. The fragmented cropland landscape greatly restricted the intensive utilisation that contributed to the decline in FP. The high density of urban buildings reduced the aesthetic value of natural landscapes and further damaged biodiversity by increasing the isolation of natural habitats [38]. Increasing the intensity and frequency of human-induced disturbance in urbanised areas could directly threaten biodiversity and reduce NPP, thus inducing a significant effect on the terrestrial ecosystem carbon cycle [38,39]. Hence, the conflicts among ES and FP, BC, CR, and CU were particularly strong in LUFB4 and LUFB2. LUFB1 and LUFB2 generally experienced trade-offs between FP and ecological functions (e.g., BC and WR) to ensure food security, which is consistent with the study conducted by Sylla et al. (2020) [40]. The negative externalities were ignored owing to the long-term pursuit of increased farmland productivity. This pursuit included the application of artificial pesticides, which aggravated the vulnerability of habitats and greatly increased demand for agricultural irrigation, which induced water shortages [40,41]. LUFB3 is far removed from the inland areas and occupies a large area of coastal wetlands and grasslands, where the land is mainly protected except for coastal industrial development. Therefore, the most common LUF interactions in LUFB3 were positive; however, strong trade-offs among ES and BC, CU, and RE were detected in 2010 and 2018, which reflected the harmful impacts of coastal harbours, industries, and reclaimed cropland on natural habitats [11,12,42,43].

The spatiotemporal intersections among multiple LUFs could not be ignored, as they can change a bundle from one type to another, thus forming diversified evolutionary trajectories. Therefore, some previous studies have proposed the use of spatiotemporal approaches to quantify the spatial trajectory of bundles to explore the dynamics of LUF interactions [22,23]. Similarly, we detected six trajectories of changes over time, representing urbanisation (LUFB1 and LUFB2 to LUFB4, LUFB1 to LUFB2), tidal flat reclamation (LUFB3 to LUFB1), and agricultural protection (LUFB2 to LUFB1, LUFB4 to LUFB2) (Figure 5c). Since the 1980s, the Jiangsu coastal area has experienced rapid urbanisation primarily characterised by large rural–urban population migrations and expansion of urban areas and the built environment. According to land-use statistics, the consequence of urban expansion was a loss of 1.57×10^3 km^2 of fertile cropland, which increased the intensity and scope of conflicts between FP and ES, RC, and TR in urban and suburban farmland [44]. Urban transportation construction directly impaired the beauty of the landscape by changing the size, shape, and interconnectivity of the natural landscape, which is why long-term trade-offs among ES, TR, and CU appeared in LUFB2 and LUFB4 [37,45]. Interestingly, beginning in 2010, a trade-off between FP and PW has occurred in LUFB1, which can be explained by the large population transfer from rural to urban areas; this has led to a decline in agricultural employment in high GDP areas [37]. Prominent conflict among ES, BC, and CU was detected in LUFB3 in 2010 and 2018, reflecting that economic growth impaired the ecological restoration capacity of coastal ecosystems, which was consistent with the conclusion of [42]. Coastal reclamation activities driven by agricultural planting, aquaculture, the salt–chemical industry, ports, and factories were the main factors [28]. Compared with the southern area, the newly reclaimed area in the north was small during the study period; in addition, an old reclamation area (located in Lianyungang) underwent a drastic land-use adjustment (from industrial land to an aquaculture pond), which explains why an opposite conflict trend among ES, BC, and CU was detected across different reclamation areas. Additionally, after 2013, a slowdown in the intensity of reclamation activities and the establishment of a national nature reserve to maintain ecological security on the eastern coast played a positive role in the improvement of BC and CU [11].

5.3. Land Use Multifunctionality: A Pathway to Sustainable Land Use

Land use multifunctionality is considered a suitable solution for realising sustainable development [3,46]. LUF quantification facilitates the evaluation of the sustainability of land changes driven by stakeholders [3]. Furthermore, the dynamics of LUF relationships directly show that human demands intervene in changes in the social-ecological system and thus affect global or regional sustainable development [8]. Therefore, it is necessary to integrate LUF estimations and their relationships into societal management decisions and land planning [47]. Recent studies have emphasised the importance of multifunctionality in land use zoning, including dividing landscapes into geographic clusters according to the similarity and interactions of LUFs [4,8,48]. Identifying land-use multifunctional zones can bring numerous benefits for policymakers and managers, as regional decisions that support sustainable development can be made with reference to the dominant LUFs and the trade-offs/synergies of each zone [22]. Our research found that LUF values and relationships did not remain the same over time; correspondingly, LUF clusters are also constantly changing [23]. Therefore, when designing intervention strategies, we should pay greater attention to the socioeconomic factors that may affect historical and current zoning results. Finally, we suggest that the orientation of land management should be shifted from a single function to multifunctional land use and that a win–win solution can be achieved by coordinating the spatiotemporal trade-offs among LUFs [4].

The specialised agricultural zone (LUFB1) is the major crop-producing area of the Jiangsu coast. This area is prominent in terms of food production, agricultural employment, and ecological regulation, and these should be maintained and expanded in future regional planning. However, in coastal cropland, the production of BC and CU increased, but FP remained almost unchanged, and ES declined. The functional values of FP and BC in cropland close to inland cities declined significantly, but the economic and social functions improved. Hence, two completely different management proposals are proposed: For coastal cropland, intensive planting can be used to ensure high food productivity, encouraging green cultivation and restricting the application of large amounts of pesticides and fertilisers. For inland cropland, it is suggested to strictly implement China's "requisition-compensation balance of farmland" policy to protect the amount of cropland, prevent superior occupation with inadequate compensation [49], restore the soil fertility and ecological conditions of cropland through agricultural fallow, and develop leisure agriculture to further improve economic and social functions.

As another major crop-producing area, the mosaic cropland-rural housing zone (LUFB2) also provides high food productivity and agricultural employment, but numerous scattered rural settlements restrict the provision of WR and BC. Therefore, the land management objectives here include optimising the configuration of rural construction land and settlements, reclaiming abandoned land, strengthening the transformation of low- and medium-yield fields, and restoring habitat quality and soil conservation.

The coastal natural and seminatural landscape zone (LUFB3) covers a large area of natural land with profuse biodiversity and high aesthetic value. Significant trade-offs between ES, BC, and CU were observed in the reclamation area, which reflected the negative external impact of coastal reclamation. Consequently, we propose strictly controlling tidal flat reclamation activities and optimising the utilisation of old reclamation areas to increase economic value, establish wetland natural and ecological reserves, build ecological corridors and isolation belts, and reform coastal industries, including abandoning high-polluting industries and strengthening port-based and new energy industries.

The urban development zone (LUFB4) has experienced rapid city expansion and economic growth, resulting in a strong conflict between economic and social-environmental functions. Moreover, the development of the southern cities currently exceeds that of the northern cities. In land planning, economic transitions and improvements in urban functions should be considered in northern cities, while southern cities should emphasise urban renewal that concentrates urban construction within city boundaries and increases intensive use. In addition, intracity green spaces should be built to improve habitat quality and landscape aesthetics.

6. Conclusions

This empirical investigation in the Jiangsu coastal area quantified and analysed the LUF dynamic characteristics (2000–2018) at a grid scale. In this research, the "bundle" concept was introduced into the LUF research framework, and the spatiotemporal effects of LUF trade-offs and synergies were creatively explored in each identified LUF bundle. First, this comprehensive assessment of LUFs in the Jiangsu coastal area shows that the distribution of various LUFs was heterogeneous across the landscape and that the overall provision of regional multifunction improved during the study period. Second, the trajectories of four spatial bundles with different dominant LUFs and landscape configurations over time revealed important processes in the development of the social-ecological system (e.g., urbanisation, coastal reclamation, and agriculture protection policies), which echoed the temporal dynamics of LUF interactions within bundles. This result implied that the "bundle" method has advantages in exploring the dynamics of LUF interactions. Finally, we highlight that considering land multifunctionality in land decision-making is a feasible means of achieving sustainability. In conclusion, our results expanded our understanding of the complex spatiotemporal interactions of multiple LUFs bundled together, and the empirical investigation of LUMFs on the coast significantly contributed to this research field. However, we also clearly recognise that examining 18 years of dynamics of LUF relationships is far from sufficient as historical analysis and that a longer timeframe is needed to determine the influence of socioeconomic factors and policies and to predict the trends of the future LUFs dynamics. This will be further refined in future work.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11020286/s1, LUF quantification method; Figure S1: Spatial distribution of eleven land use functions in 2000 and 2010 by the quintiles; Figure S2: Map of trends in grid values of land use functions across the Jiangsu coastal area from 2000 to 2018; Figure S3: Spatial variations in factor scores of trade-offs and synergies among multiple provided functions in four bundles (2000, 2010); Table S1: Changes and area proportion in LUMF and LUFs by trend types; Table S2: The diversity scores (number of effective LUFs) of each bundle in 2000, 2010 and 2018 respectively; Table S3: The main trade-offs and synergies among LUFs in each cluster.

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