RESEARCH ARTICLE

# Integrating ecosystem services, stakeholders' perspective, and land-use scenarios to safeguard sustainability of the Mulberry-Dyke and Fish-Pond System

**Jingya Lin · Lu Huang · Yihong Zheng · Chongzhi Chen · Li Wang · Ke Wang · Jiangxiao Qiu**

## Abstract

*Context* Optimizing landscape patterns by considering ecosystem services and human well-being is crucial for landscape sustainability research. Such optimization process shall also consider multiple stakeholders' perspectives, interests and benefits, which remain less well investigated.

*Objectives* The study aims to integrate ecosystem services and land-use scenario analysis to design sustainable landscapes. The overall goal of spatial optimization is to explore pathways towards sustainable development.

*Methods* This study uses the Mulberry-Dyke and Fish-Pond System as a representative agricultural landscape. It analyzes the spatiotemporal pattern of the landscape from 1975 to 2019. The market value method, InVEST model, and MaxEnt model are used to quantify the ecosystem services of the landscape. The analytic hierarchy process is used to set the weight of ecosystem services from the perspective of three stakeholder groups. We compare the outcomes of different scenarios and assessed through emergy yield ratio, environmental loading ratio, and environmental sustainability index.

*Results* Our results indicated that: (1) The scale of the Mulberry-Dyke and Fish-Pond system decreased significantly from 1975 to 2019. (2) Among the six major ecosystem services, the average value of water purification service was the highest, while average value of mulberry supply service was the lowest. (3)

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Spatial optimization of the three design objectives, 'sustainably intensify', 'increase landscape multifunctionality', and 'restore ecological integrity', were primarily distributed in the study area's eastern, central, and western regions, respectively. (4) All three stakeholder-oriented scenarios showed improvements in ecological quality or agricultural output.

*Conclusions* Our study incorporates viewpoints of critical, diverse stakeholders in the assessment of ecosystem services and scenario analysis to establish sustainable and culturally important agricultural landscape. The framework and methods can help minimize environmental stress on the system, balance agricultural productivity and profitability, and enhance the sustainability of agricultural landscapes.

**Keywords** Landscape sustainability · Spatial optimization · Ecosystem services · Multifunctional landscape · Participation · Scenario simulation

## Introduction

Across the world, generations of farmers and herders have created, developed, and managed diverse agricultural systems based on the resources and technologies available at the time (Koohafkan and Altieri 2011). These traditional systems not only generate unique agricultural landscapes (Manrique Anticona et al. 2023), but also provide a wide range of goods and services, ensuring food security and community resilience, and improving people's quality of life (Piras and Santoro 2023; Fagerholm et al. 2016; Wang et al. 2021). Over time, these agricultural systems have been designed and managed where synergistic interactions are manifested among agricultural production, rural livelihoods, biodiversity, social organizations, cultural landscapes, and innovation, collectively generating sustainable human activities that co-adapt with the environment (Liu et al. 2018). With the global trend towards industrialization and intensification of agriculture, the area of traditional agriculture and associated labor force are shrinking (Miyake et al. 2021). The loss of the traditional agricultural system poses complex social, economic, and environmental challenges to the local communities, further disrupting human-nature relations, and leading to impacts at different spatial scales (García-Martín et al. 2022; Riechers et al. 2020).

Recent studies have shown that a place-based and use-inspired approach to understanding and improving the dynamic relationship between landscape patterns, ecosystem services, and human well-being is a promising research direction for rethinking landscape sustainability (Wu 2013, 2021; Zhou et al. 2019). Hence, promoting ecological intensification and multifunctionality can be important strategies that lead to the development of sustainable and multifunctional agricultural landscapes (Wittwer et al. 2021; García-Martín et al. 2022; MacLaren et al. 2022). Ecosystem services, as the link between ecosystems and socio-economic systems, have been widely used to explore and understand multifunctionality of agricultural landscapes (Mouchet et al. 2017; Manning et al. 2018; Hölting et al. 2019). Several methods have been developed to quantify landscape multifunctionality, such as "multiple ecosystem services landscape index" to map the provisioning of ecosystem services (Rodriguez-Loinaz et al. 2015), "ecosystem services richness index" to show the total number of ecosystem services (Powers et al. 2020), and a number of landscape diversity indices such as Simpson's reciprocal index and Shannon's H′ index, which aim to quantify the provision of ecosystem services and their diversity (Sturck and Verburg 2017). Despite their usefulness, a limitation of these methods is that they do not incorporate stakeholder preferences into the process of assessing landscape multifunctionality. Different social groups hold varying opinions on ecosystem services, presumably due to their differences in ecological worldview, inherent values, demographics, and interactions and experience with nature (Teixeira et al. 2018; Wardropper et al. 2020), leading to different optimization outcomes for multifunctionality. This is particularly evident in agricultural landscape planning, which involves multiple stakeholders (e.g., farmers, resource managers, conservationists, policymakers) due to the complexity of land ownership and contentiousness of agricultural development (Díaz et al. 2006; Wang et al. 2021).

Many European Union members have publicly expressed their goal and set up the agenda of improving multifunctionality of landscape planning (van Zanten et al. 2014). Quantitative assessments of ecosystem services and use of scenarios have gained popularity in evaluating consequences of current and future landscape changes for multifunctionality (Oteros-Rozas et al. 2015; Li et al. 2023). Indeed, in

actual spatial planning, it is crucial to involve stakeholders at every stage of the process and fully consider their attitudes, preferences, and perceptions towards ecosystem services (e.g., through participatory and knowledge co-production process) (Reed et al. 2020; Do et al. 2021). Participatory planning may promote citizen involvement in a bottom-up approach and enable stakeholders to work together to generate innovative ideas for sustainable landscapes (Xu et al. 2020; Kyttä et al. 2023). By integrating ecosystem services with participatory planning processes, new approaches to spatial decision-making and optimization in agricultural landscapes can be developed, adopted and implemented as desirable developmental pathways to achieve landscape sustainability (Van Berkel and Verburg 2014; Tran et al. 2023). To facilitate collaboration and knowledge co-production among different stakeholders and to predict future landscapes, it is necessary to integrate different models (Cohen-Shacham et al. 2019). Specific types of participatory modelling have emerged in the last few decades (Basco-Carrera et al. 2017), such as participatory modelling using system dynamics (Videira et al. 2009; Stave 2010), bayesian networks (Carmona et al. 2013), computer-aided dispute resolution (Langsdale et al. 2013), and collaborative modelling using networked environments for stakeholder participation (Evers et al. 2012). However, challenges remain in how to effectively incorporate stakeholder input into predictive modeling frameworks.

Globally Important Agricultural Heritage System has potential to return large-scale chemical-dominated industrialized agriculture into an agroecological systems that are within the bound of "safe operating space" (MacLaren et al. 2022), and secure the livelihoods of smallholder farmers (Speelman et al. 2014). China's Mulberry-Dyke and Fish-Pond System (MFS), recognized as a "Globally Important Agricultural Heritage System" in 2017 (FAO 2017), is one such example that has characteristics of closed-loop and regenerative agriculture. MFS was originated more than 2500 years ago and still works as a typical circular agriculture in many regions of China. Its practice is characterized as "raising silkworms with mulberry leaves, feeding fish with silkworm feces, and fertilizing mulberries with pond mud". MFS systems have been unique integrated agroecosystems given their potential capacities to recycle wastes, energy, and nutrients, adapt to extremely limited farm

areas, store soil carbon and mitigate climate change, and provide subsistence for poor rural households (Li and Min 1999). MFS, developed based on local experience, traditional ecological and indigenous knowledge, has facilitated the rapid development of the local agricultural economy and fostered the prosperity of the Huzhou Basin, as well as advocated for us in many other developing counties as integrated farming practices (Wu et al. 2018). To a large extent, MFS played a fundamental role in the historical agricultural development in China. However, like other traditional agricultural systems worldwide, MFS faces challenges such as labor shortages and the need for intensive aquaculture in fisheries and sericulture to keep up with urbanization, rising human demands, and pressures from industrial development (Zhang et al. 2019a). Due to the desire for higher economic returns, farmers are increasingly abandoning sericulture in favor of expanding pond areas (Nie et al. 2003). This shift has resulted in a significant decrease in the dyke-pond ratio (Zhou et al. 2023), tipping balances in their productions and thus compromising their long-term sustainability. It is noteworthy that the listed Globally Important Agricultural Heritage Systems by the United Nations Food and Agriculture Organization has stimulated policy interventions, academic research and raised interest from outsiders (FAO 2002; Zhang et al. 2019b). In the case of MFS, being selected as an important agricultural cultural heritage has incentivized the local communities to be proud of their agricultural heritage, rediscover their cultural values, and rethink and reignite agrarian production as a practice that is in harmony with nature (Gu et al. 2022a). Although this international recognition has increased the sales volume of products produced in traditional agriculture (Martins et al. 2022), in the process of urbanization, much agricultural lands have been lost to urban development and expansion of construction areas. Further, agricultural landscapes are demonstrating an increasing tendency towards monoculture at their core to maximize yield and ease management (Li et al. 2021).

Hence, in this study, we aim to integrate ecosystem services, stakeholders' perspectives, and land-use scenarios to inform spatial optimization to achieve landscape sustainability of MFS systems. The focal MFS reserve is located in the center of the Yangtze River Delta urban agglomeration, one of China's most developed areas. On the one hand, the local and provincial

government tries to preserve the traditional farming culture, but at the same time faces pressure for land development. Revitalizing the multifunctionality of traditional agriculture such as for the MFS, can not only help coordinate the above conflicts but also crucial to the preservation of cultural landscapes and inform development of modern agriculture (Bjørkhaug and Richards 2008). Such understanding requires more work on the effects of MFS on ecosystem services so that it can be better integrated into landscape and urban planning to reconcile the needs for conserving natural capital, enhancing agricultural production, and improving life quality and rural livelihoods, consequently achieving landscape sustainability. We specifically aim to address the following research questions: (1) What are the current provision of ecosystem services, their landscape multifunctionality, and hotspots and coldspots of the MFS system? (2) What are the spatial–temporal dynamics of MFS from 1975 to 2019, and how will MFS change under alternative future planning scenarios? (3) What are the consequences of alternative land-use scenarios of MFS development for landscape sustainability? To answer question #1, the study involved local stakeholders in determining ecosystem services that are highly valued and contribute most to their well-being (Cowling et al. 2008), and used mixed methods to quantify six ecosystem services from MFS. We then calculated ecosystem service multifunctionality based on results of weighted ecosystem services preference survey from different stakeholder groups, and further mapped spatial variations in hotspots and coldspots of ecosystem services. These results of ecosystem services and multifunctionality were then used to determine different functional zones and inform spatial optimization and land-use scenarios development (question #2). The scenarios were then assessed using multiple sustainability indicators related to stakeholder well-being (question #3). This study aims to reconcile human demands and environmental protection by linking ecosystem services, spatial patterns, and human well-being, to create more sustainable and equitable traditional agricultural landscapes.

## Methods

### Study area

Our study region, Nanxun District, is located in the center of the Yangtze River Delta urban agglomeration (i.e., one of the most economically developed regions in China) and on the southern shore of the Taihu basin in Zhejiang Province (120°05'-120°26' E, 30°43'-30°58' N). This region represents the most concentrated, largest, and best-preserved MFS production systems in China (Fig. 1). The area has a flat terrain and dense river network system, making it a typical plain river network region. The climate of the study region is subtropical monsoon characterized with four distinct seasons, with averaged annual temperature of 17.8–18.2 °C, annual precipitation of 1,348–1,723 mm, humidity of 74%, and sunshine duration of 41% (between 2020 and 2022). The year-round warm and humid climate makes it suitable for crop cultivation and aquaculture production.

Nanxun District, covering 8 towns and 2 sub-districts, had a total area of 702.26 km² and a registered population of 486,400 in 2022, of which 430,000 were rural residents. Major agricultural activities in the area include freshwater fish farming, rice cultivation, and silkworm cocoon production. In 2014, the Huzhou Municipal Government proposed the "Huzhou Mulberry-Dyke & Fish-Pond System Protection and Development Planning" (The People's Government of Nanxun District 2017), which defined the conservation area of the Huzhou MFS (FAO 2017) (Fig. 1), as an attempt to mitigate the loss and degradation of the MFS.

### Data collection

The land use/cover data for 2019 were obtained from Huzhou Bureau of Natural Resources and Planning (Table 1). Keyhole satellite imageries for 1975, and Tiandi imageries for 2000 and 2015, were utilized to extract the land use data. Based on the "Classification of Land Use Status" (Ministry of natural resources of the people 's republic of china 2017) issued by China on 1 November 2017, and the actual situation of the study area, we classified the land use/cover types into six groups: mulberry fields, fish ponds, paddy fields, construction land, unutilized land, and other agricultural land (Fig. 5). We sampled 100 examples of each land use/cover type. These samples were divided into training and testing sets based on a 7:3 stratified random sampling method. Using the spectral and textural features of the remote sensing images, we employed the maximum likelihood method (He et al.
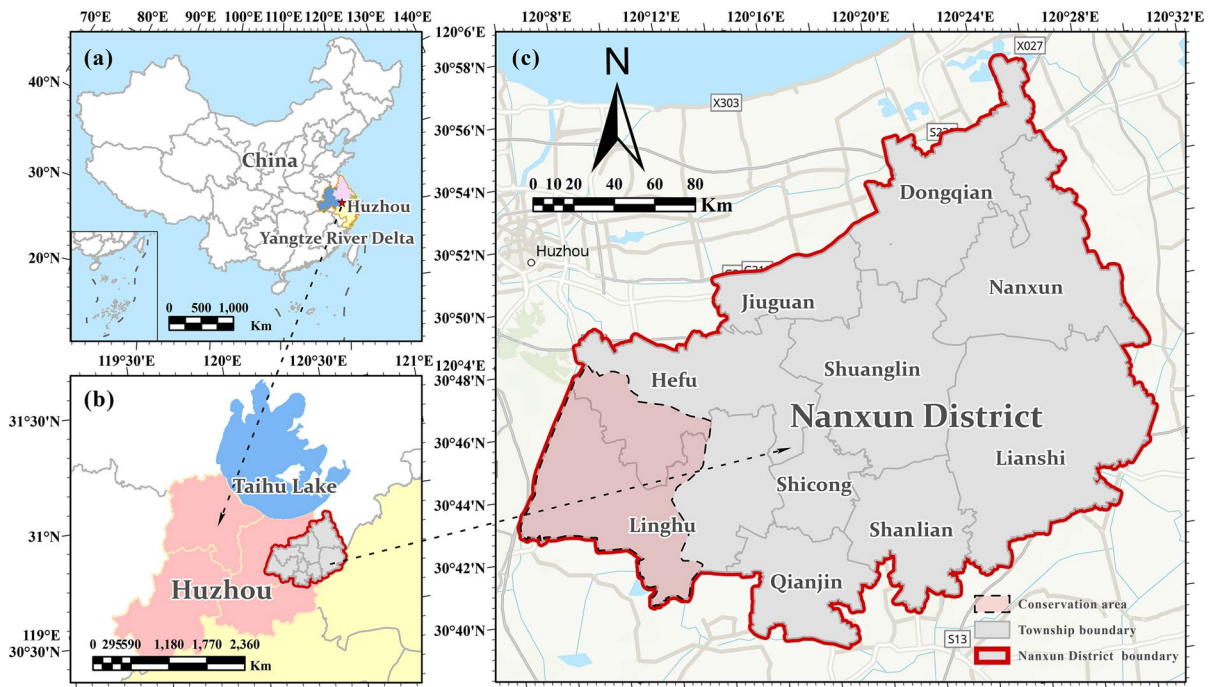
**Fig. 1** Location of the study area

2018) to supervise the classification of the training set using ENVI 5.3 software. The overall accuracy and the kappa coefficient of the test set in the confusion matrix both exceeded 0.8, which met the requirements of the study.

In addition to land use data, we also collected other socioeconomic data, environmental data, and planning data to meet the needs of ecosystem service assessment and future model simulations. Slope and aspect information were extracted from DEM data. The distance from the water system, main road, and built-up area was calculated by the ArcGIS 10.8 Euclidean distance tool. All data were referenced and aligned to a unified and consistent coordinate system, with spatial resolution of 30 m × 30 m.

Research framework and workflow

The study included four main steps to address our research questions (Fig. 2). Specifically, to address our question #1 (i.e., Step 1 in Fig. 2), six ecosystem services were chosen and quantified by different methods, including market valuation,

InVEST modeling, and MaxEnt. Based on results from preference survey on perspectives of different stakeholder groups, the six ecosystem services were weighted by the Analytic Hierarchy Process (AHP) (Saaty 1988) and aggregated to calculate ecosystem service multifunctionality. To address our question #2 (i.e., Steps 2 and 3 in Fig. 2), the land use dynamic index was first utilized to analyze the spatiotemporal changes of MFS from 1975 to 2019. In addition, four scenarios of future land use dynamics (up to 2035) were simulated using the Markov model and the Future Land Use Simulation Model (FLUS). It is worth noting that (a) the assessment and weighting of ES from Step 1 provided the basis for spatial optimization and setting transition probabilities in Step 3; and (b) different design goals derived from the multifunctionality and hotspot analyses from Step 1 (Table 3 below) were applied to develop three of the stakeholder-oriented scenarios in Step 3. Finally, to answer our question #3, future land-use scenarios of MFS were further assessment (i.e., Step 4 in Fig. 2) through integrated social-ecological indicators, including emergy yield ratio, environmental

**Table 1** Data sources in this study

| Data Type | Data | Year | Resolution | Sources |
|---|---|---|---|---|
| Geographic data | land use and land cover (LULC) | 2019 | 1:10,000 | Huzhou Bureau of Natural Resources and Planning (http://huzgt.huzhou.gov.cn/; accessed on 15 February 2023) |
| | KeyHole satellite imagery | 1975 | 4 m | China Centre for Resources Satellite Data and Application (http://www.cresda.com/) |
| | Tiandi imagery | 2000, 2015 | 1 m | National Platform for Common Geospatial Information Services (https://www.tianditu.gov.cn/; accessed on 3 February 2023) |
| | DEM | 2019 | 30 m | Geospatial Data Cloud (http://www.gscloud.cn/; accessed on 15 April 2022) |
| | Water system | 2019 | – | Open street map (http://www.openstreetmap.org/; accessed on 20 January 2023) |
| Environmental data | Monthly precipitation | 2020 | 1 km | National Earth System Science Data Center (http://www.geodata.cn/; accessed on 3 February 2023) |
| | Temperature | | | |
| | Evaporation | | | |
| Socioeconomic data | GDP | 2019 | 1 km | Resource and Environment Science Data Center of Chinese Academy of Sciences (http://www.resdc.cn/; accessed on 15 January 2023) |
| | Population | | 100 m | Worldpop (https://www.worldpop.org/; accessed on 26 January 2023) |
| | Agricultural input and output in production systems | | – | Field investigation (accessed on 15 April 2022) |
| | POI | | – | Open Application Program Interface of Gaode Map Platform (https://lbs.amap.com/; accessed on 28 November 2019) |
| | Primary road/secondary road | | – | Open street map (http://www.openstreetmap.org/; accessed on 20 January 2023) |
| | Highway | | – | |
| | Rural settlements | | – | National Geomatics Center of China (https://www.ngcc.cn/; accessed on 20 January 2023) |
| | Governments | | – | |
| | Built up area | | – | |
| Planning data | Ecological redlines | 2019 | 1:10,000 | Huzhou Bureau of Natural Resources and Planning (http://huzgt.huzhou.gov.cn/; accessed on 15 February 2023) |
| | Permanent farmland redlines | | | |

loading ratio, and environmental sustainability index.

Ecosystem services mapping and assessment

*Selection and quantification of ecosystem services*

Based on the classification of ecosystem services (Millennium Ecosystem Assessment 2005) and the relevant literature of MFS, six ecosystem services were chosen belonging to three categories (i.e., provisioning, regulating, and cultural services) (Table 2). Provisioning services included the production of mulberry and fish, where field work was conducted to

obtain data on annual yield per unit area of fishponds and mulberry fields, as well as their average prices of these two agricultural communities (Supplementary S1). These data were then combined with land use data to segment the fishnets and estimate potential supply. Regulating services included purifying water quality and conserving water sources, because MFS can purify pollutants such as N and P in water bodies, and provide a large amount of nutrients for aquaculture. Water purification is estimated using nitrogen leaching as an inverse indicator of freshwater (Powers et al. 2020). The aquatic plants in the pond play a role in intercepting, absorbing, and infiltrating precipitation, preventing surface runoff and avoiding geological
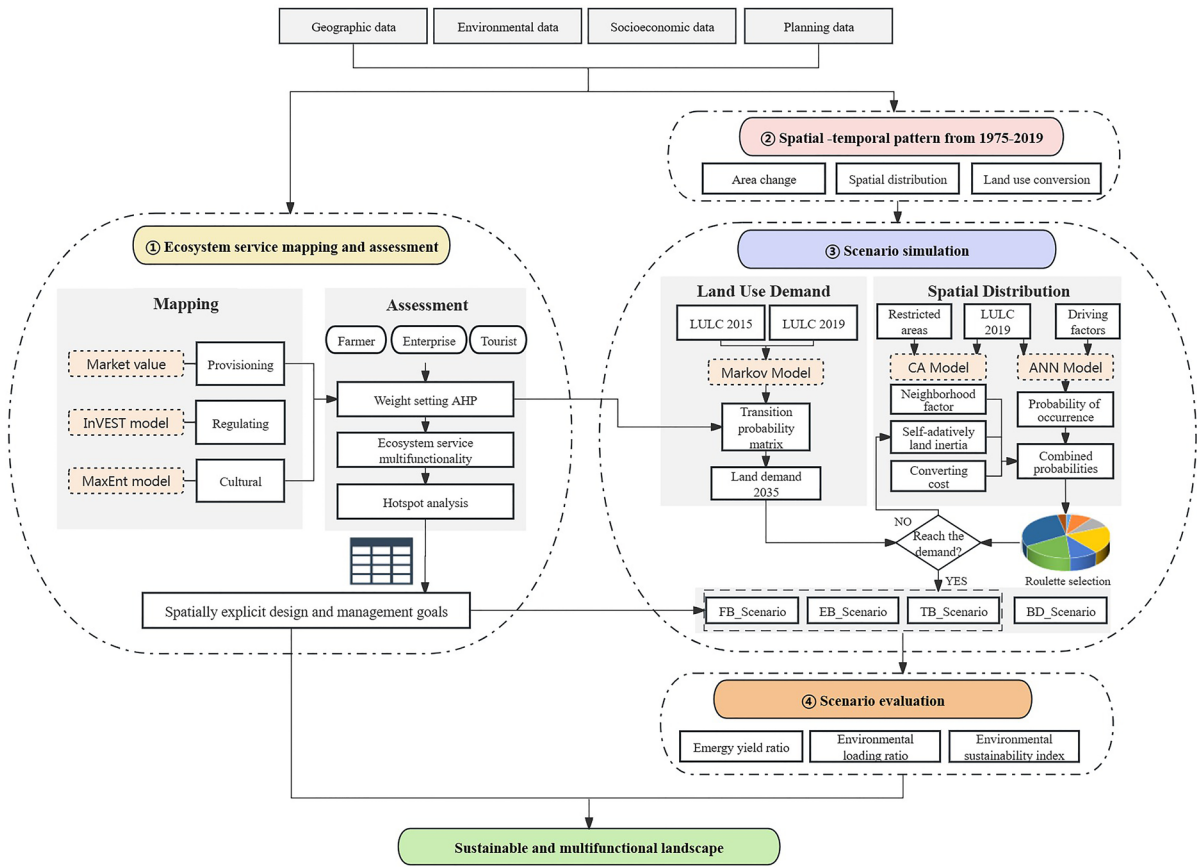
**Fig. 2** Flow chart of the research

**Table 2** Quantifying and weight setting of ecosystem services

| Ecosystem services category | Ecosystem services | Weighting | | | | | | Calculation method | Descriptions |
|---|---|---|---|---|---|---|---|---|---|
| | | Farmer | | Enterprise | | Tourist | | | |
| Provisioning services | Mulberry product | 0.51 | 0.12 | 0.17 | 0.38 | 0.12 | 0.22 | $V_P = \frac{\sum(P_i \times PV_i) - c}{A}$ | See the note |
| | Fish product | | 0.88 | | 0.62 | | 0.78 | | |
| Regulating services | Water purification | 0.37 | 0.80 | 0.45 | 0.66 | 0.30 | 0.36 | InVEST model | (Redhead et al. 2018; Li et al. 2021, 2023) |
| | Water conservation | | 0.20 | | 0.34 | | 0.64 | | |
| Cultural services | Recreation | 0.12 | 0.88 | 0.38 | 0.67 | 0.58 | 0.78 | Maxent model | (Phillips et al. 2006; Richards and Friess 2015) |
| | Inspirational | | 0.12 | | 0.34 | | 0.22 | | |

Note: i represents different products; *P* is the annual average production of the product; *PV* is the market average price of the product; *c* is the annual average total production cost; *A* is the area

disasters such as flash floods. The MaxEnt model was used to quantify cultural services utilizing "scenic spots" point of interest (POI) data obtained from the

Amap platform in 2019 as sample points, and select six environmental variables, including land use, slope, distance to water sources, distance to roads, distance

**Table 3** Prioritizing landscape design goals (modified from Tran et al. (2023))

| Level of ecosystem services provision | | Regulating services | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | High | NS | Low | High | NS | Low | High | NS | Low |
| Provisioning services | High | G1 | G2 | G2 | G3 | G3 | G3 | G2 | G3 | G3 |
| | NS | G1 | G1 | G2 | G1 | G2 | G3 | G2 | G3 | G3 |
| | Low | G1 | G1 | G2 | G1 | G1 | G1 | G2 | G2 | G3 |
| Cultural services | | High | | | NS | | | Low | | |

High indicates hot spots (i.e., high value zone) of the corresponding ecosystem service; NS indicates not significant; Low indicates cold spots (i.e., low value zone) of the corresponding ecosystem service

to accommodations, and distance to administrative centers, from both natural and anthropogenic aspects.

### *Assessment of ecosystem services multifunctionality and hotspots*

Since ecosystem services are quantified in different units, the min–max method is used to normalize the values of all ecosystem services to the range of 0–1 for subsequent analyses. To account for the contribution of different management objectives and priorities to ecosystem service multifunctionality, a weighted approach is employed using the AHP (Vaidya and Kumar 2006), taking into account the preferences of three main stakeholder groups. Specifically, we conducted a comprehensive survey, where a total of 73 participants (24 farmers, 22 employees of local enterprises, 27 tourists) were randomly selected to rank the importance of ecosystem services according to their preferences. A 1–9 point scale is used to construct a judgment matrix (Supplementary S2–S5), and the weight of each factor is calculated (Table 2). The weighted ecosystem services layers are summed to create the ecosystem service multifunctionality index layer. Finally, hotspot analysis is performed using the Getis-Ord Gi algorithm tool in ArcGIS 10.8 to identify hot spots and cold spots within the ecosystem service multifunctionality index layer. Ecosystem service multifunctionality is considered to be in the high value zone if Z score > 1.64 and in the low value zone if Z score < − 1.64 (Ord and Getis 2010).

### Land use dynamics

Land use dynamics refers to the overall structural change rate of land use/cover types in a specific period in a certain area. Compared with other dynamic research methods, this method can reflect the degree to which human activities affect the ecological environment in a simple and direct manner (He and Sikor 2015). This study utilized land use dynamics to analyze the intensity of changes in land use types from 1975 to 2019. The calculation formula showed as follows:

$$K = \frac{(U_b - U_a)}{U_a} \times \frac{1}{T} \times 100\% \tag{1}$$

where K represents the land use dynamics of a certain land use type during the study period; $U_a$ represents the quantity of a certain land use type at the beginning of the study period; $U_b$ represents the quantity of a certain land use type at the end of the study period; $T$ represents the duration of the study period.

### Scenario simulation of future land use

### *Scenario setting and goal setting*

This paper sets four future land-use scenarios for Nanxun District by 2035: Baseline Development Scenario (BD), Farmer-based Scenario (FB), Enterprise-based Scenario (EB), and Tourist-based Scenario (TB). The Baseline Development Scenario (BD) is constructed by assuming that current economic and demographic development and technological innovation trends will remain consistent, taking the land use status in 2019 as the baseline data. The other three scenarios were set according to the "National Economic and Social Development 14th Five-Year Plan and 2035 Vision Outline of Nanxun District, Huzhou City", which prioritizes the protection of ecological space, high-quality utilization of urban space, and intensive utilization of agricultural areas. FB is

an agriculture production-oriented land use scenario favored by farmers. It followed the ecosystem service weightings of farmers (Table 2) and aimed to maximize economic benefits through intensive agricultural production. EB followed the ecosystem service weightings of enterprises (Table 2), and strengthened the protection and inheritance of the globally important agricultural heritage system. TB followed the ecosystem service weightings of tourists (Table 2). The scenario adjusted and optimized the urban land layout to meet the needs of cultural services, by accelerating the redevelopment of underutilized urban land and enhancing the attractiveness of scenic spots.

Each stakeholder-oriented scenario (FB, EB and TB) encompasses three distinct design goals, "sustainable intensification" (G1), "increase landscape multifunctionality" (G2), and "restore ecological integrity" (G3) (Landis 2017; Tran et al. 2023). Based on the current assessment of ecosystem service provision (Sect. 2.4.2), the spatial analysis tool in ArcGIS was used to create a spatial layer aggregating all hots and cold spot polygons and an attribute table containing all attributes in the ES hot spot maps. Design goals were then assigned to the study area using the field calculator functionality in ArcGIS (Table 3). These design and management goals enable landscape designers to quickly identify, for a given scenario, areas where future land use or management changes are needed to meet each of the three goals, providing the basis for scenario-based zoning in the following FLUS simulation. In other words, how G1–G3 were spatially distributed in the FLUS simulation varied by each scenario. Specifically,

G1 represents agricultural areas with relatively low yields, which can be balanced by increasing service provision while maintaining existing regulation and cultural services. The design goal is to increase agricultural production service while maintaining current levels of other services.

G2 areas typically have lower yields, but other services are well supplied. The design goal is to increase overall multifunctionality of ecosystem service.

G3 areas usually occur in suitable cultivation regions with technological advantages, highly intensive agricultural practices, but low levels of regulation and cultural services. The design goal is to restore ecological integrity while mitigating negative ecological impacts while maintaining high yields.

### Demand prediction based on Markov model

Based on the land use/cover data in 2015 and 2019, the Markov model was used to predict the land demand for BD in 2035 (Arsanjani et al. 2013). To predict the land demand for FB, EB and TB scenarios in 2035, the land use transition probability matrix was adjusted (Table 4) based on the transition probability from 2015 to 2019, and the preference of stakeholders (Table 2). Specifically, the G1's design goals aim to increase agricultural production services by expanding the area of fish ponds and mulberry fields while minimizing the likelihood of these areas transitioning to other land types. The transfer probability values were determined based on the stakeholder preference survey results (Table 2). For instance, in the ecosystem service of fish products, farmers showed the highest preference for fish farming, resulting in the highest disincentive to convert fish ponds to construction land when setting transfer probabilities. It is noted (*) that as the probability of fish ponds to mulberry gardens is extremely small, the probability

| Table 4 Land use transition probability | Zoning | Land use conversion | FB | EB | TB |
|---|---|---|---|---|---|
| | | | Transition probability | | |
| | G1 | Fish pond—Construction land | − 60% | − 10% | − 20% |
| | | Mulberry field, paddy field—Construction land | − 40% | − 50% | − 30% |
| | G2 | Various land types—Construction land | − 50% | − 30% | − 10% |
| "−" means reduce based on the transition probability from 2015 to 2019, while "+" means increase based on the transition probability from 2015 to 2019 | | Unused land—Mulberry field | + 10% | + 50% | + 10% |
| | G3 | Fish pond—Mulberry field* | 1% | 0.5% | 1% |
| | | Fish pond—Paddy field, other agricultural land | + 20% | + 60% | + 10% |
| | | Mulberry field, paddy field, other agricultural land—Construction land | − 40% | − 60% | − 30% |

of fish ponds to mulberry fields in G3 zoning areas for FB and TB was set to be 1%, and the probability of transfer for EB was set to be 0.5%. Then the land demand under the four scenarios in 2035 was determined (Table 5).

*Parameter setting in FLUS model*

To spatially distribute the future demand to each grid, the study adopted the FLUS model, which incorporated the probability of occurrence with the neighborhood factor, conversion cost, restricted areas and self-adaptive land inertia to estimate the combined probability for each land grid (Liu et al. 2017). To calculate the probability-of-occurrence of each land use type, this study selects 12 driving force factors to build an Artificial Neural Network model of the probability for each landscape type. Natural factors include elevation, slope, and aspect. Socio-economic factors include population and GDP. Locational factors include the distance to highways, main road, secondary trunk road, administrative center, built-up area, rural settlements, and water system. The neighborhood factor represents the ability of certain land use types to expand into other land types. The range of the factor is set to 0–1: the closer the value is to 1, the stronger the expansion ability of that land use type is (Liang et al. 2021). Based on previous studies and combined with the characteristics of the study area, fish pond, mulberry field, paddy field, construction land, other agricultural land, and unutilized land are assigned values of 1, 0.52, 0, 0.75, 0.51, and 0.56, respectively (Wang et al. 2019). The conversion cost matrix indicates whether the classes in each region can be converted to each other, with 1 indicating that it can be converted and 0 indicating that it cannot. With the development of social economy, existing science and technology, construction land is less likely to be converted to other land types. Therefore, it is stipulated that construction land shall not be converted to other land categories. Additionally, in the G3 zone, there are restrictions on the conversion of mulberry fields to other land categories. Each scenario sets permanent basic farmland and ecological protection red lines proposed by the government as restricted areas (Table 1). The self-adaptive land inertia coefficient was defined to auto-adjust the inheritance of the land on each grid cell, which is according to the differences between future areas and current areas (iteratively changed).

*Accuracy verification*

Land use maps in 2000 and 2015 were used to simulate land use in 2019, and the actual land use map in 2019 was used to assess model performance and simulation accuracy. The OA value and Kappa coefficient were 0.90 and 0.88, respectively, indicating

**Table 5** Number of predicted land use grids in 2035

| Scenario | | Fish pond | Mulberry field | Paddy field | Construction land | Other agricultural land | Unutilized land |
|---|---|---|---|---|---|---|---|
| BD | | 253,754 | 87,538 | 87,626 | 215,883 | 38,265 | 97,219 |
| FB | | 243,528 | 93,351 | 96,501 | 209,428 | 40,141 | 97,336 |
| | G1 | 55,763 | 53,119 | 82,515 | 152,765 | 23,256 | 48,415 |
| | G2 | 48,967 | 13,783 | 8211 | 26,420 | 7206 | 15,493 |
| | G3 | 138,798 | 26,449 | 5775 | 30,243 | 9679 | 33,428 |
| EB | | 228,271 | 97,830 | 106,129 | 211,981 | 39,773 | 96,301 |
| | G1 | 48,817 | 53,811 | 86,364 | 152,174 | 20,878 | 46,506 |
| | G2 | 51,260 | 17,091 | 12,708 | 29,644 | 10,365 | 17,388 |
| | G3 | 128,194 | 26,928 | 7057 | 30,163 | 8530 | 32,407 |
| TB | | 225,023 | 94,759 | 104,210 | 229,494 | 39,498 | 87,301 |
| | G1 | 46,345 | 52,042 | 83,986 | 168,770 | 22,224 | 43,697 |
| | G2 | 43,239 | 15,788 | 14,374 | 29,957 | 9304 | 15,451 |
| | G3 | 135,439 | 26,929 | 5850 | 30,767 | 7970 | 28,153 |

that the model simulation had high reliability (Zhang et al. 2011).

## Assessing sustainability of land-use scenarios

To assess the sustainability of future land-use scenarios, this study utilized energy analysis and emergy indicators to quantify the ecological and economic effects of the four scenarios. An energy analysis table (Supplementary S6) is developed based on the collection of relevant primary data, using fixed calculation formulas, energy conversion coefficients, and energy transformation coefficients from works by Odum (1988, 1996), Chen (2006), Gu (2022b), and Agricultural Technology and Economic Manual (Technical and Economic Agricultural Manual Editorial Board 1983). The main energy inputs and outputs of the system were calculated, and the energy input of the research system was classified into four categories: renewable environmental resources (R), non-renewable environmental resources (N), non-renewable purchased industrial auxiliary energy (F), and renewable organic energy (T). The energy output is divided into economic output energy (Y1) and waste output energy (Y2).

Based on the energy analysis of different agricultural production types, this study establishes emergy indicators to evaluate the ecological and economic benefits of scenarios. The emergy indicators are as follows:

(1) Emergy Yield Ratio (EYR) is the ratio of the total output emergy of the system to the input emergy of social and economic feedback. It is used to measure the ability of the agricultural production system to use natural resources and its resource utilization efficiency. The higher the emergy yield ratio, the greater the dependence of the agricultural production system on natural resources and the higher the resource utilization efficiency.

$$EYR = (Y1 + Y2)/(F + T) \tag{2}$$

(2) Environmental Loading Ratio (ELR) is the ratio of the total energy value of non-renewable energy inputs in the system to the total energy value of renewable energy inputs. It is used to measure the potential pressure of the agricultural production system on the environment. The higher the environmental loading ratio, the greater the pressure of the agricultural production system on the local environment, and the less sustainable it is.

$$ELR = (F + N)/(R + T) \tag{3}$$

(3) Environmental Sustainability Index (ESI) is the ratio of EYR to ELR. The ESI reflects not only the intensity of economic growth, but also the environmental pressure on natural ecosystems. It could measure the sustainability of the agricultural production system. The higher the index value, the more sustainable the agricultural production system is (Ascione et al. 2009; Huang et al. 2018).

$$ESI = EYR/ELR \tag{4}$$

## Results

### Landscape multifunctionality

In 2019, six ecosystem services exhibited significant spatial heterogeneity throughout the landscape (Fig. 3a). In descending order of their average values for our study region, these services were water purification (0.83), water retention (0.60), inspirational (0.25), fish product (0.24), recreation (0.16), and mulberry product (0.13). Among them, the degree of spatial variation in services was highest for fish products and lowest for mulberry products (Fig. 3b). The spatial pattern of multifunctionality by ecosystem service category under three weighting preferences was illustrated (Fig. 3c).

According to the hot spot analysis, the three categories of services all exhibited overall consistency in hot and cold spot patterns of ecosystem service multifunctionality under three preference weights by stakeholders (Fig. 4). Specifically, compared with the weightings for enterprises and tourists, the weighting scheme for farmers showed a greater concentration of hot and cold spots. The hot spots of provisioning services were concentrated in the western region, and the cold spots were in the eastern region. In terms of area, the cold spot regions in the weighting scheme for farmers (38,080 ha) were larger than those in the weighting schemes for enterprises and tourists
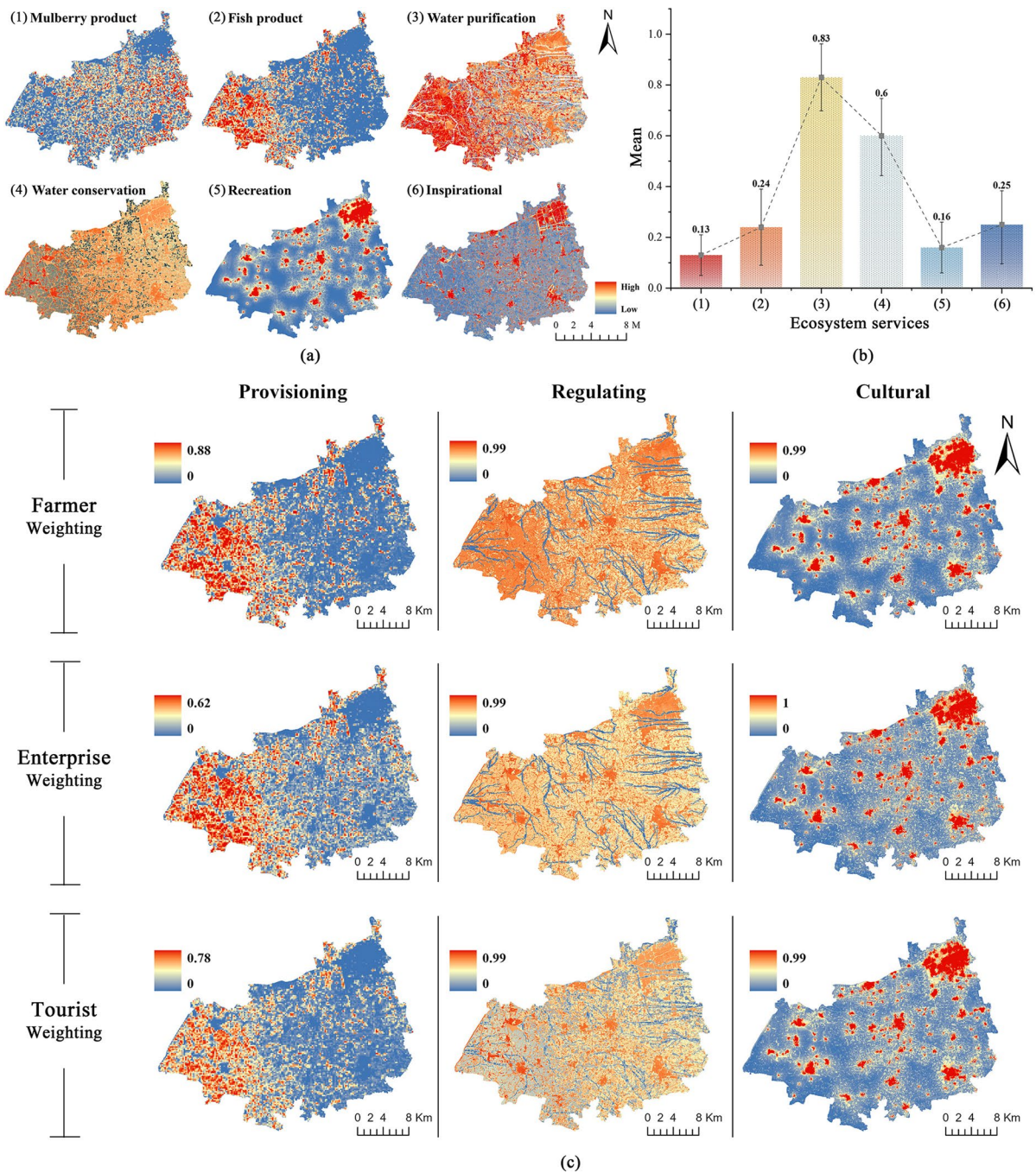
**Fig. 3** **a** Spatial pattern of six ecosystem services in 2019, and **b** calculated the mean and standard deviation of each ecosystem service values; **c** Ecosystem service multifunctionality index in the study area

(33,576 ha and 34,440 ha respectively). Hot and cold spots of regulating services were mainly determined by water quality. In the weighting scheme for farmers, the fish pond area in the western part of Nanxun had a high level of regulating services. The patterns of cold and hot spots of cultural services in the three weighting schemes were highly consistent, gradually weakening from the northeast towards the southwest edge.
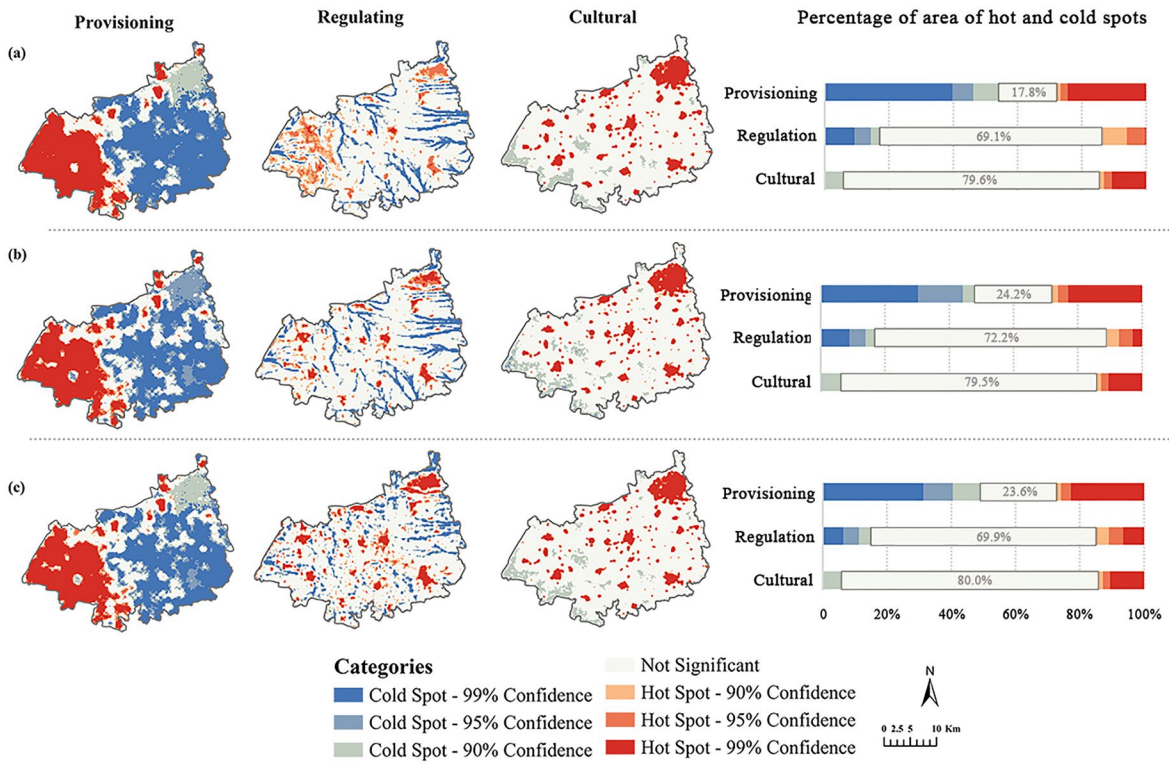
**Fig. 4** Hot spots and cold spots of ecosystem services provision in the study area: **a** farmer's weighting, **b** enterprise's weighting, and **c** tourist's weighting

Hot spots were mainly distributed in regions with a certain foundation for tourism development and public awareness.

Spatial and temporal pattern of MFS

From 1975 to 2019, the area of fish ponds and mulberry fields was significantly reduced and fragmented. At present, relatively intact MFS is mainly concentrated in the western part of Nanxun District (Fig. 5). From 2000 to 2019, fish ponds increased significantly, with an additional 8,783 hectares. In 2019, fish ponds accounted for the largest proportion of land use in Nanxun District (23.91%) (Table 6). Starting from the western part of the study area, the scale of fish pond aquaculture expanded outward, and gradually became the main agricultural system in the study area. From 2000 to 2019, mulberry fields experienced a significant decrease, with an area reduction of 5,138 hectares. The area of mulberry fields was large in 1975 and 2000, but it gradually became scattered and fragmented, with no apparent spatial aggregation areas in 2019.

Scenario simulation of MFS in 2035

Since the priorities of ecosystem services largely depend on specific land use management goals, we employed paired comparisons to establish three design objectives for the study area (Fig. 6). The G1 zoning area was mainly distributed in paddy fields and urbanized areas in the east. The G2 zoning area was mainly distributed in the transition area among fish ponds, mulberry fields, and paddy fields, scattered in the central region. The G3 zoning area was dominated by fish ponds and was spatially concentrated in the western part of Nanxun District, with a large overlap with the conservation area of the globally important agricultural heritage system recognized by the Food and Agriculture Organization of the United Nations.
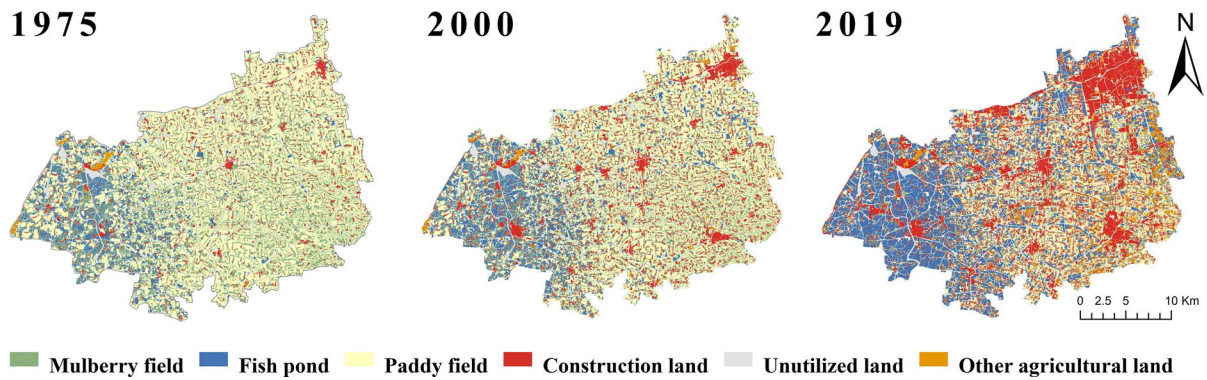
**Fig. 5** Pattern of MFS landscape in 1975, 2000, and 2019

The spatial changes under different scenarios were mainly concentrated in the conservation area of MFS in 2019 (Fig. 7a). Overall, the land use dynamics of the BD were much higher than those of other scenarios. Among the four scenarios, the land use type with the greatest change was the paddy field (Table 6). In BD, the area of mulberry fields decreased significantly, while the area of fish ponds and construction land continued to expand. A large number of paddy fields were converted into construction land, and agricultural land such as mulberry fields decreased (Fig. 7b). In FB, the expansion rate of fish ponds increased, mainly due to the conversion of paddy fields. In EB, the area of mulberry fields remained stable in 2035, while the area of fish ponds increased by 3,757.05 hm² compared with that in 2019. In TB, the area of fish ponds was well controlled, with only a 1.29% increase, while it had the largest increase in construction land compared to the other three scenarios.

Sustainability assessment for scenarios

The emergy analysis of MFS showed that the EB scenario had exhibited the highest level of emergy inputs and outputs, with a total input emergy of $1.05 \times 10^{21}$ Sej and a corresponding total output emergy of $8.15 \times 10^{21}$ Sej (Table 7). Economic output was constituted a core component of the emergy yield, thereby indicating a favorable economic performance under the EB scenario. Moreover, there were only minor structural differences in the patterns of emergy inputs and outputs between the FB and EB. The more detailed calculations of the emergy inputs and outputs of the scenarios were shown in Supplementary S6. From the perspective of economic benefits, when a system has a high production capacity and economic efficiency, it exhibits a high emergy yield ratio (Fig. 8). EB had the highest EYR, which was 39.21% higher than that of BD. The EYR of FB was 28.32% higher than that of BD. In terms of environmental benefits, FB and EB performed better than BD and TB in ecological protection. In terms of sustainability, the ESI ranged between 1 and 10, indicating that all four scenarios had strong development potential (Brown and Ulgiati 1997). Specifically, EB and FB had stronger sustainability than BD and TB. The ESI for EB and FB improves in 2035 compared to 2019.

## Discussion

### Sustainability of multifunctional agricultural landscapes

Prior research has confirmed the significance of spatial arrangement of landscape elements in allowing for more effective circulation of materials and energy across the landscape. For example, the vertically distributed landscape pattern exhibited by the Hani terraced landscapes successfully achieves effective irrigation for the terraces, thereby promoting a synergistic coupled water and energy cycling within the region (Cao et al. 2013). Similarly, the typical spatial structure embodied in the Xinghua Duotian

**Table 6** Land use/cover changes in the study area from 1975 to 2035 (Area unit: hm²)

| Type | 1975 | 2000 | 2019 | 2035 | | | | Land-use dynamic index/% (2019–2035) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | BD | FB | EB | TB | BD | FB | EB | TB |
| Dyke-pond ratio | – | – | 3.4:6.6 | 2.5:7.5 | 2.8:7.3 | 3:7 | 2.9:7.1 | – | – | – | – |
| Fish pond | 5484.72 | 8004.16 | 16,787.34 | 22,837.86 | 21,917.52 | 20,544.39 | 20,252.07 | 2.36 | 1.91 | 1.40 | 1.29 |
| Mulberry field | 16,047.00 | 13,932.91 | 8794.8 | 7878.42 | 8401.59 | 8804.7 | 8528.31 | -0.76 | -0.28 | 0.01 | -0.19 |
| Paddy field | 35,297.67 | 29,650.29 | 15,185.07 | 7886.34 | 8685.09 | 9551.61 | 9378.90 | -3.01 | -2.68 | -2.32 | -2.39 |
| Construction land | 3688.11 | 8639.97 | 16,455.96 | 19,429.47 | 18,848.52 | 19,078.29 | 20,654.46 | 1.12 | 0.91 | 1.00 | 1.59 |
| Other agricultural land | 1096.91 | 1569.20 | 4385.43 | 3443.85 | 3612.69 | 3579.57 | 3554.82 | -1.41 | -1.10 | -1.15 | -1.18 |
| Unutilized land | 8611.66 | 8429.55 | 8617.05 | 8749.71 | 8760.24 | 8667.09 | 7857.09 | 0.02 | 0.10 | 0.04 | -0.55 |

Agrosystem promotes efficient allocation and utilization of water and soil resources, thereby facilitating material flow and energy cycling (Li et al. 2020). This study demonstrates the significant impact of spatial patterns on material cycles and energy flows in MFS landscapes. In highly simplified landscapes dominated by fishponds, dyke-pond ratio directly affects nutrient exchange and energy flow between land and water (Zhong 1987). Research on MFS in the Pearl River Delta in the 1960s indicated that the optimal dyke-pond ratio was 3:7 from the ecological and material cycling perspective. This study confirmed this result. Among the four scenarios, the EB's fish pond area was relatively small, with a dyke-pond ratio close to 3:7 (Table 6). Compared with intensive aquaculture ponds, the EB scenario enhanced the aquatic environment of fish ponds, thereby improving fish quality and market values. Therefore, even with a significant difference in fish pond areas, the EYR of EB were 39.21% higher than that of BD (Sect. 3.4). Meanwhile, according to O Cavalett et al. (2006), if the ELR of the system is less than 2, there is no significant environmental impact during the production process. The ELRs of FB and EB were less than 2. Hence the ESI of EB exceeded those of other scenarios (Fig. 8, Supplementary S6). The scenario evaluation results indicate that EB has huge potential for sustainable development. The ESI of FB were close to those of EB, suggesting that local farmers and enterprises have strong environmental awareness and their shared values have been fostered through socialization within the same environment and culture (Massenberg 2019), ultimately achieving a win–win situation between ecological protection and economic growth. The evaluation results of FB were slightly weaker than those of EB. However, from the perspective of farmers, expanding fish pond areas to obtain higher profits would be more conducive to implementation.

Making appropriate land management decisions can help create multifunctional landscapes and enhance the sustainability of landscapes dominated by human activities (Waldhardt et al. 2010; Schindler et al. 2014). "The Protection of the Mulberry-Dyke and Fish-Pond System in Huzhou City" (Standing Committee of the National People's Congress of Huzhou City 2023) proposed the organization of resource surveys for MFS, implementing classified management, and coordinating the development of
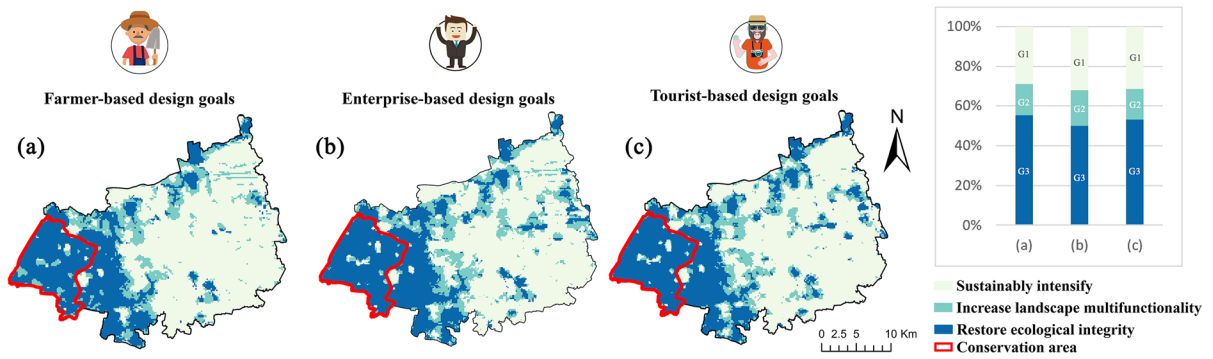
**Fig. 6** Spatially explicit design and management goals
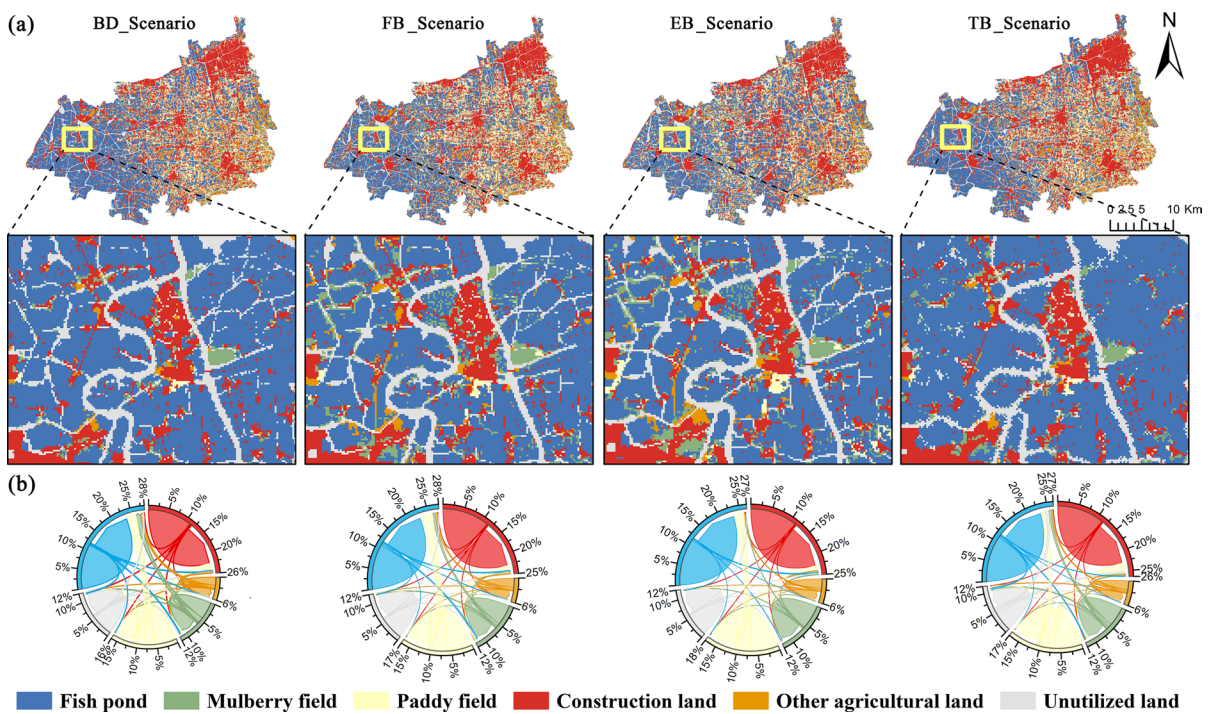


**Fig. 7** Spatial distribution and transition chord diagram of Nanxun District in 2035

specialized plans for the protection and development of MFS. Based on the scenario assessment, as well as the feedback from various stakeholders, the study could help guide spatial planning and management for different zones (Sect. 2.6.1). G1 zoning area recommends further concentrating core fishery areas while reducing and optimizing fish ponds outside of these areas. This approach aims to maintain the economic benefits generated by aquaculture while minimizing potential pollution risks to the environment, thereby

achieving the dual objectives of ensuring food production and promoting farmers' income. G2 zoning area utilizes various material, biological, and cultural resources related to MFS to construct a new type of circular agriculture in the MFS landscape. G3 zoning area focuses on aggregating the main areas in MFS that provide diverse ecosystem services, involving establishing appropriate access criteria and limiting large-scale human activities to support the sustainable development of MFS. The target setting and relative

**Table 7** Emergy structure analysis for MFS under different scenarios

| | Project | 2019 Emergy Value (Sej) | 2035 Emergy Value (Sej) | | | |
|---|---|---|---|---|---|---|
| | | | BD | FB | EB | TB |
| Input | R | 1.88E+19 | 2.26E+19 | 2.23E+19 | 2.16E+19 | 2.12E+19 |
| | N | 2.07E+19 | 1.85E+19 | 1.98E+19 | 2.07E+19 | 2.01E+19 |
| | F | 5.05E+20 | 6.12E+20 | 5.96E+20 | 5.72E+20 | 5.71E+20 |
| | T | 1.75E+20 | 1.97E+20 | 3.83E+20 | 4.39E+20 | 1.79E+20 |
| | Total | 7.19E+20 | 8.50E+20 | 1.02E+21 | 1.05E+21 | 7.91E+20 |
| Output | Y1 | 3.58E+21 | 4.67E+21 | 7.26E+21 | 8.13E+21 | 4.98E+21 |
| | Y2 | 1.50E+19 | 1.35E+19 | 1.44E+19 | 1.51E+19 | 1.46E+19 |
| | Total | 3.60E+21 | 4.68E+21 | 7.27E+21 | 8.15E+21 | 4.99E+21 |
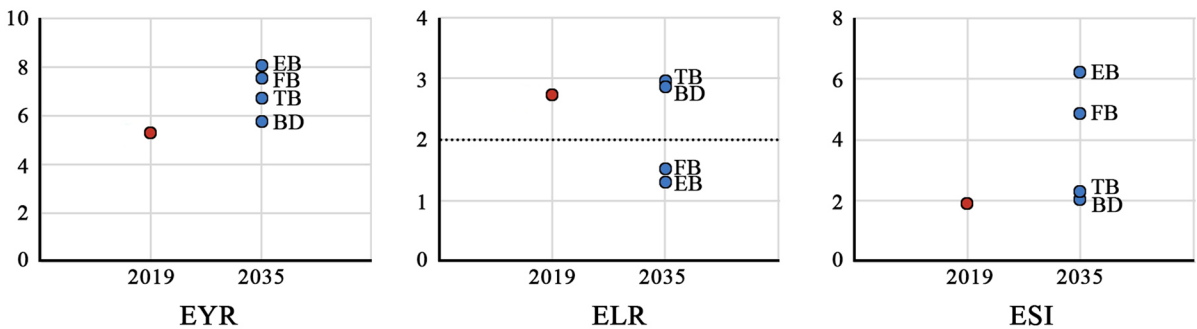


**Fig. 8** Results of Scenario Evaluation. The red dots represent the value of EYR, ELR, and ESI in 2019; the blue dots represent the value of EYR, ELR, and ESI in 2035

zoning strategies will implement differentiated spatial management, help the government to make rural development decisions at different planning stages (e.g., vision, strategy, national territory spatial planning), and guide multiple stakeholders toward a sustainable and multifunctional MFS landscape.

### Research framework for participatory planning

Stakeholder needs for multifunctional landscapes can vary. For example, farmers may prioritize the potential for service provision, while tourists may be more interested in preserving landscape diversity (Manning et al. 2018). Therefore, local engagement and absorption of information by policymakers are crucial to achieving sustainable landscapes (Howard et al. 2013; Wu 2021). Engaging diverse stakeholders in the design of multifunctional agricultural landscapes may increase the adoption of land use strategies (Butler et al. 2014; Speelman et al. 2014). The creation of land use scenarios can bridge the gap among workers, operators, and consumers (Welp et al. 2006) and

maximize the rationality of decision-making research (Seppelt et al. 2011). The stakeholders considered in this study are closely associated with MFS landscapes, including farmers, enterprises, and tourists, who live in and experience MFS landscapes every day. Their participation enhances the applicability and adoption of sustainable landscape planning based on the relationship between ecosystem services and landscape patterns.

However, translating qualitative descriptions of stakeholders input into quantitative data and applying them to simulate scenarios pose great challenges (Alcamo 2008; Vukomanovic et al. 2023). Several methodological novelties in this work worth mentoring. Few studies have incorporated stakeholder preferences in a step-by-step manner into each phase of planning. In this study, stakeholder opinions are fully integrated in all three aspects of zoning management, scenario setting, and model parameter setting. (1) The quantification of ecosystem services is essential for the formulation of regional environmental management policies (Pinke et al. 2018). Our method differs

slightly from the one suggested by Manning et al. (2018) as our weighting factors do not reflect actual benefits, but the perceived importance of ecosystem services. This study uniquely combined extensive stakeholder input with various quantifiable biophysical models of ecosystem services to translate stakeholders' qualitative descriptions of the future into quantitative spatial information. We integrated public opinion and the experience of the three main stakeholder groups and made pairwise comparisons of each ecosystem service across all scenarios to identify different priorities for future landscapes. This revealed consensus and conflicting preferences regarding future landscape visions and strategies (Jiren et al. 2023). Based on these preference outcomes, further spatial analysis was performed using tools in ArcGIS to derive zoning for design objectives. The establishment of ecosystem services based zoning provides a basis for spatial analysis. 2) In scenario construction, most study develops future scenarios from the perspective of policy objectives such as agricultural production (Iverson Nassauer and Corry 2004), climate change (LeBrun et al. 2017) and ecological protection (Ding et al. 2021) to outline different development strategies. However, the process tends to lack input from stakeholders in the forecasting process. MFS landscape scenarios have been formulated with stakeholders as the main actors to improve the acceptance of landscape planning outcomes. (3) In simulating future land use patterns, the current model requires researchers to inevitably incorporate their professional expertise and practical experience into the parameter adjustment process to fully adapt to specific regional characteristics and meet forecast demands. For instance, varying perceptions among different researchers regarding the transition probabilities for a certain type of land use transformation may lead to distinct weight assignments in the model configuration (Zhang et al. 2020). To avoid the subjectivity of model parameter setting, this study incorporated the quantitative results of ecosystem service preferences into the scenario setting by considering perspectives of different dominant stakeholder groups. The weighted preferences of different stakeholders obtained through the AHP are used as a basis for determining the probability of land use transfer in the FLUS model. This research framework combines scientific knowledge with stakeholder perspectives, using both qualitative and quantitative methods to

explore different future possibilities. Such analyses and processes help to reduce conflicts and contradictions between stakeholders and to design more sustainable and multifunctional agricultural landscapes.

### Advantages and uncertainties of spatial optimization from the perspective of ecosystem service multifunctionality

Searching for sustainable landscape patterns should be a unifying theme for all landscape-related studies (Wu 2021). Integrating ecosystem service and their multifunctionality into spatial planning, and combining spatial optimization with scenario analysis offers a more efficient solution to explore pathways towards achieving landscape sustainability (Seppelt et al. 2013; Almenar et al. 2018). This study provides an empirical case to illustrate how land-change projections (FLUS) and ecosystem services modeling (InVEST, MaxEnt) can be integrated to translate storylines into trajectories of landscape design, planning, and optimization to identify the location and quantity of desired outcomes. The relationship between various ecosystem services and landscape pattern changes was clarified, and the heterogeneity of different ecosystem services provided by spatial units was fully considered. A set of optimization solutions has been developed using ecosystem services, spatial simulation, and scenario sustainability assessment (Fig. 2). These linkages between patterns, ecosystem services, human well-being, and stakeholder involvement effectively promote sustainable landscape planning.

Uncertainty is ubiquitous in spatial and landscape planning that may pose limitations to this work (Neuendorf et al. 2018). Firstly, uncertainty could originate from data source. This study aims to optimize spatial configurations for a multifunctional agricultural landscape using 2019 land use/cover data from China's Third National Land Survey, which is authoritative, most recent with highest accuracy (Qu et al. 2021; Chen et al. 2022). Hence, rapid changes in land use/cover since 2019 due to demographic shifts and intensive agriculture could not be captured in this dataset, calling for the need of using technologies like satellite remote sensing and machine learning (Awad 2018; Talukdar et al. 2020) to capture and automate recent, complex environmental and land cover changes to improve the accuracy of future simulations. The second source of uncertainty stems from

the choice of indicators. The selection of evaluation indicators greatly affects the final multifunctionality analysis, and changing or adding indicators will definitely alter the results (Hou et al. 2013). This study takes into account the spatial heterogeneity resulting from the interaction of landscape multifunctionality and to avoid the bias towards specific service types. Subsequently, three system-level ecosystem service indicators are utilized to assess and compare sustainability outcomes of different scenarios. Nevertheless, while we have deliberately selected our indicators of ecosystem services and sustainability assessments, our results and findings will likely subject to changes in alternative choices of metrics. Thirdly, to avoid the subjectivity of model parameter setting, this study incorporated the quantitative results of ecosystem service preferences into the scenario setting by considering perspectives of different dominant stakeholder groups. However, due to a certain degree of consistency in the stakeholder weighting schemes, it resulted in substantial similarity in the design goal maps (Fig. 6). In future research, participatory mapping approaches and complementary qualitative methods can be employed to gain a deeper understanding of potential areas of benefit or conflict so as to better capture more nuanced and fine-scale spatial heterogeneity (Fagerholm et al. 2012; Chan et al. 2012; Karimi and Brown 2017; Riechers et al. 2017). Moreover, we expect that in larger and more culturally diverse regions with different value systems, the assessments of ecosystem service values by different stakeholders will show more pronounced discrepancies.

## Conclusion

This study integrated diverse stakeholders' perspectives in ecosystem service assessment and scenario analysis to establish a sustainable agricultural landscape. Quantification of ecosystem services indicated significant differences among the six services within the MFS landscape, with water purification service having the highest mean value. The spatial distribution of three development goals was identified by weighting and quantifying the preferences of different stakeholders for ecosystem services. The goal of creating a multifunctional landscape with sustainable intensification was primarily concentrated

in the eastern region, which was characterized by paddy field coverage and urbanization. The areas with increased landscape multifunctionality were dispersed in the central area, whereas areas for restoring ecological integrity were concentrated in the western part of Nanxun District, largely overlapping with the core protection zone of globally recognized important agricultural cultural heritage endorsed by the Food and Agriculture Organization of the United Nations. Given accelerated shrinkage of the MFS landscape, the study holistically considered diverse opinions of leading stakeholders, including farmers, enterprises, and tourists, as well as ecosystem service multifunctionality, to simulate the spatial pattern in 2035. Although stakeholders may have different priorities, the ecological quality and agricultural output both improved compared to the baseline development scenario. The enterprise-led sustainability indicators yielded the highest outcomes. The sustainability assessment of scenarios suggests that the MFS landscape performs best in sustainability when the dyke-pond ratio approaches 3:7. This study presents a methodological framework that can be applied to other contexts and systems to integrate ecosystem services, stakeholders' perspectives, and land-use scenarios to achieve landscape sustainability. The results of this work also provide theoretical guidance for delineating spatial functional zones of landscapes, and have direct policy implications by informing sustainable land management and development.

**Author contributions** JL analyzed the data and wrote the manuscript, LH proposed the research idea and revised the manuscript, YZ, CC and LW collected and analyzed the data, KW commented on the manuscript, and JQ revised the manuscript. All authors read and approved the final manuscript.

**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

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