Received: 7 March 2023 | Revised: 16 November 2023 | Accepted: 18 November 2023

DOI: 10.1002/ppp3.10479

RESEARCH ARTICLE

Plants People Planet PPP Open Access

Preserving traditional systems: Identification of agricultural heritage areas based on agro-biodiversity

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Funding information
Beijing Innovation Consortium of Agriculture Research System, Grant/Award Number: BAIC09-2023

Societal Impact Statement

With the rapid development of modern agriculture and its reliance on high-yielding and genetically uniform varieties, many traditional agricultural systems are gradually being abandoned. The genetic diversity contained in landraces is crucial for modern eco-agriculture. An indicator evaluation model combined with machine learning could help to locate and conserve these existing traditional agricultural systems, called agricultural heritage systems (AHS). Here, this method provided the first map of potential areas of Tea-AHS in China. These results could help policymakers to confirm priorities and rationally allocate conservation resources based on the distribution status and endangerment of AHS. This could also help local people to receive additional support for the transfer of germplasm resources and indigenous knowledge.

Summary

- Modern agriculture is overly dependent on high-yielding and genetically uniform varieties, whereas traditional agricultural systems contain a large number of genetically diverse landraces and the indigenous knowledge associated with them. We call traditional agricultural systems that survive to the present-day agricultural heritage systems (AHS). Under the impact of modernization, AHS are gradually disappearing. Identifying these systems is the first step towards conserving them, but the potential areas of AHS related to agro-biodiversity are not yet clear.
- Using Chinese tea as an example, this paper provides the first universal method for identifying potential areas of AHS based on agro-biodiversity and the first map of potential areas of Tea-AHS in China. The map is constructed based on the maximum entropy model (Maxent) of tea germplasm resources and related indicator functions and has been validated by existing Tea-AHS in China.
- The study identified 54 potential areas of Tea-AHS. These potential areas are mainly concentrated in the southern region, in 15 provinces, including Anhui, Fujian, Guangdong, Yunnan, Guizhou, Guangxi, Hubei, and Hunan. Mangshi, Qimen County, and Chaisang District are among the high potential areas for Tea-AHS and are the next priority for exploration and conservation work.

- We have verified the validity of the proposed method, which can help conserve the germplasm resources and traditional wisdom in the global AHS in a timely manner, and contribute to the development of modern and eco-agriculture.

KEYWORDS
agricultural heritage systems, agro-biodiversity, identification of potential distribution areas, Maxent, traditional agriculture systems

1 | INTRODUCTION

Due to the progress of science and the development of society, large-scale farming represented by modernization and mechanization is the main system of agricultural production in the world today. However, traditional agricultural systems still have their unique value and should be conserved (Antonelli, 2023; FAO, 2021). Germplasm resources are of fundamental and strategic importance for food security, and a study of 27 crops in eight countries on five continents showed that traditional agricultural systems maintain considerable food genetic diversity (Jarvis et al., 2008). Traditional farmers conserve the landraces of many crops, such as rice (Pusadee et al., 2009), maize (Perales et al., 2005), figs (Achtak et al., 2010), and indigenous animals (Boettcher & Hoffmann, 2011; Ren et al., 2018). Moreover, traditional agricultural systems often organically combine the production of crops, fruits, fisheries, and livestock, and this coupling also maximizes the use of resources. In the Mulberry-dyke & Fish-pond System, which originated in China 2000 years ago, fish are kept in ponds, and mulberry is planted in pond banks. Mulberry leaves can be fed to silkworms, and silkworm excrement can be used to feed fish. Fish manure can be used to fertilize the ponds, and the pond sludge in turn fertilizes the mulberry (Astudillo et al., 2015; Ruddle et al., 1983). This ecological cycle greatly reduces the system's dependence on external chemicals and increases the biodiversity of the system while improving the efficiency of resource use (Liu et al., 2013). In addition, due to their high ecological sustainability and environmental adaptability, traditional agricultural systems are often also of great relevance for farmland types such as depressions, hills, oases, and slopes (which account for about 5.8% of the world's farmland) (Wang et al., 2022) and other farmland types where it is difficult to carry out large-scale cultivation.

Over time, human farming civilizations have created many traditional agricultural systems that combine livelihoods, biodiversity, and resilient ecosystems (Drinkwater et al., 1998). Some of these systems still exist today, and we call them agricultural heritage systems (AHS). The most important feature of these diverse types of AHS is that each of them has been formed through long-term synergistic evolution and dynamic adaptation to its environment (Altieri & Koohafkan, 2004). For example, drought-tolerant jujube trees are planted on the loess plateau where soil and water conditions are poor; a production lifestyle that integrates nomadic herding, farming, hunting, and woodcutting is formed at the interface of alpine grasslands, temperate grasslands, and warm temperate deciduous forests; and a jasmine-tea stereo agriculture system is established in areas where wetlands and mountains coexist (Globally Important Agricultural Heritage Systems, GIAHS, n.d.). Pioneers balance economic and ecological benefits by selecting landraces with high native suitability, rational land use patterns, and clever production combinations (e.g., natural cycles, crop rotation, and intercropping) (Levis et al., 2017). Numerous studies have shown that AHS have unique advantages in addressing climate change (Drinkwater et al., 1998), conserving biodiversity (Lao et al., 2022; Ren et al., 2018), and providing ecosystem services (Gurr et al., 2016; Yuan et al., 2022). To promote the conservation, transmission, and development of this heritage on a global scale, FAO launched a dynamic conservation and adaptive management project of GIAHS in 2002 (Altieri & Koohafkan, 2004). Subsequently, China (Jiao et al., 2021), Japan (Akira & Evonne, 2021), Korea, and other countries have also undertaken conservation work on National Important Agricultural Heritage Systems (NIAHS).

AHS can be broadly classified into two groups based on the core elements being conserved. One group focuses on the conservation of sustainable land use practices, which can also be referred to as human-agricultural systems, such as terraced systems and rice-fish-duck systems (Liu et al., 2006). The interactions between crops, humans, and ecosystems and the associated flow of nutrients and energy in these systems are the key point of their ecological value and traditional wisdom (Cruz & Koohafkan, 2009). The other group focuses on the conservation of agro-biodiversity in traditional systems. They often contain a variety of landraces, but each AHS has a core conservation objective (i.e., the core germplasm resources). Examples include jujube in the Jiaxian Traditional Chinese Date Gardens and Pu'er in the Pu'er Traditional Tea Agrosystem in Yunnan. Around the core germplasm resources, these systems have also developed integrated features that take into account smallholder livelihoods (Liu et al., 2018), indigenous knowledge, and traditional culture (Kohsaka et al., 2019). More and more researchers have recognized the need for germplasm diversity in traditional agricultural systems for food security, and the genetic diversity contained in traditional landraces is crucial for the modern seed industry, the future development of agricultural science, and technological innovation (Ren et al., 2018).

However, these systems also face multiple threats, such as climate change (Wang et al., 2022) and increased competition for natural resources. In addition, with rapid economic development, modern agriculture has become overly dependent on high-yielding and genetically uniform varieties. A large number of traditional agricultural methods and landraces have been abandoned, and many traditional agricultural systems have disappeared (Altieri & Koohafkan, 2004;

GIAHS, n.d.). As more of the valuable knowledge and germplasm resources inherent in traditional agriculture are lost, it is important for researchers to identify in a timely manner where potential agricultural heritage areas are, especially those with core germplasm resources. The identification of such areas could inspire general policies orientated a wider range of areas, while such research could contribute to the design of genetic diversity conservation and sustainable agricultural systems that integrate traditional knowledge and modern technologies. The comprehensive understanding of the distribution status and endangerment of traditional agricultural systems would also help to confirm conservation priorities, rationally allocate conservation resources, and increase efficiency.

Investigating potential AHS areas on a large scale through field surveys is labor intensive, while this bottom-up approach relies heavily on organizational efficiency, technical support capacity, and subjective understanding of the concepts in each region. In contrast, identifying potential areas through models is a more practical assessment tool today. Scholars have explored various research methods to identify potential areas. There are three main common methods, the first of which is the indicator evaluation model. For example, Yu et al. (2018) identified potential areas for national park construction in China by constructing an indicator evaluation model, evaluating a single element layer and overlaying a multi-indicator spatial analysis, respectively. The second method is the regression approach: a classic example of a regression model is the generalized linear model, which expresses multidimensional spatial environmental elements in terms of linear parameters (Ding et al., 2019). The third is machine learning. For example, Hao et al. (2019) used a random forest approach to predict potential risk areas for terrorist attacks in the central southern peninsula at a spatial scale with 15 drivers. Coro and Trumpy (2020) used a maximum entropy model (Maxent) to identify geographically suitable areas for thermal power plants at a global scale. However, few existing studies have focused on identifying potential areas of AHS. The distribution of traditional germplasm resources, which is important for identifying areas of AHS based on agro-biodiversity, is often influenced by a variety of factors such as climate, soil, and topography, as well as more microscopic indicators within them. However, local smallholder livelihoods, traditional knowledge, and culture, which depend on germplasm resources, are also important features of AHS. Therefore, this study couples the indicator evaluation model with machine learning, which can take into account the multifaceted indicators that should be present in the agricultural heritage areas, while including the powerful data coverage and analysis capabilities of the machine learning model.

Above all, we develop a method to identify potential areas of AHS based on agro-biodiversity. The study refines the characteristics of GIAHS proposed by FAO into an indicator system (GIAHS, n.d.). Among the rich diversity and adaptability of AHS, the core germplasm resources of the system are selected as the entry point for identification (priority factor), taking into account the socio-economic factors such as farmers' livelihoods, related local knowledge and traditional culture that depend on the cultivation of the core germplasm resources (Table 1). Finally, the study verifies the method using Chinese tea as an example and provides the first map of potential areas that can be developed based on Tea-AHS, which is validated by existing Tea-AHS. Our method is generalizable to allow future identification of the potential distribution of global agro-biodiversity based on global base data. Thus, the germplasms and traditional eco-wisdom in AHS can be protected in a timely manner, bringing inspiration, theoretical basis, and practical techniques for modern ecological agriculture.

2 | MATERIALS AND METHODS

2.1 | General method

"Global importance" is a comprehensive criterion for the selection of GIAHS by FAO, which includes agro-biodiversity, food and livelihood security, local knowledge systems, traditional cultures systems, and landscapes and seascapes features (GIAHS, n.d.). Agro-biodiversity means that the system should contain globally important agro-biodiversity and genetic resources, with emphasis on the transmission and conservation of traditional germplasm resources; food and livelihood security means that the agricultural system contributes to the food or livelihood security of local communities and to rural economic development; local knowledge systems means that the AHS contains valuable traditional knowledge and practices, ingenious adaptive technologies, and natural resource management systems; traditional culture systems means that there is a rooted cultural identity and sense of presence and value system in the agricultural heritage site; landscapes and seascapes features are locally stable landscape features that have evolved and interacted over time (GIAHS, n.d.). It is generally accepted that agro-biodiversity, with traditional germplasm resources as the core, is the priority factor for identifying AHS. On this basis, socio-economic factors such as local livelihoods, traditional knowledge, and associated cultural systems that have developed around the germplasm must also be considered. Landscapes and seascapes features are essentially the outward expression of local land use practices or germplasm resources, indigenous knowledge, and culture. It is the presence of germplasm resources and the associated socio-economic factors that lead to the expression of certain landscape features at the system level. Therefore, it is more appropriate to include them as a necessary step in the subsequent assessment rather than in the initial identification process. Moreover, it is worth noting that our selection of indicators is in one-to-one correspondence with the characteristics of the GIAHS proposed by FAO. GIAHS, as the most influential project for the conservation of traditional agricultural systems in the world, has been optimizing its standards for 20 years and has consolidated the efforts of numerous experts. Therefore, it is feasible and scientific for us to use the characteristics of GIAHS as the index framework for the study.

This study is divided into three steps. First, we needed to identify the potential distribution of germplasm resources for core conservation in the AHS. The study introduced Maxent, an ecological niche model based on machine learning and maximum entropy principles (Phillips et al., 2006). Coordinates of germplasm origins were obtained

TABLE 1 An indicator system for identifying potential areas of agricultural heritage systems (AHS) based on agro-biodiversity.

The features of globally important agricultural heritage systems by FAO		Indicator	Role	Value
Priority factor	Agro-biodiversity	Germplasm resources	The germplasm resource is a core conservation element of AHS and a core component of what constitutes agro-biodiversity	Suitability score for the growth and distribution of the germplasm resource
Socio-economic factors	Food and livelihood security	Agricultural production	The core agricultural products of AHS are produced not only for the farmers' food security, but also for their livelihood through market transactions	Yield or production value; number of smallholders involved, etc.
	Local knowledge systems	Traditional knowledge Ingenious adaptive technology Management systems of natural resources	Describe the current status of invaluable local and traditional knowledge, ingenious adaptive technologies, and natural resource management systems, including biota, land and water, that have supported agricultural, forestry and/or fisheries activities	Variety selection, plantation management, harvesting techniques, garden management, traditional medicine or snacks related to germplasm resources, etc.
	Traditional culture systems	Social organizations Value systems Cultural practices	Describe how cultural identity and a sense of place are embedded in and belong to the site of AHS	Social organizations, folk literature, traditional music, traditional dance, traditional drama, opera, traditional sports, amusements and acrobatics, traditional art, folklore or other cultural forms related to germplasm resources, etc.

from data platforms as training samples for the model, and factors closely related to species distribution were also collected as a set of environmental variables. Maxent allows the identification of potential germplasm areas based on the relationship between their current incomplete distribution and environmental variables (Phillips et al., 2017). The suitability score *P* of the germplasm growth distribution predicted by the model takes a range of values [0, 1], which can generally be divided into four classes according to the natural partitioning method: $P < .25$ is a non-potential zone, $0.25 \le P < .50$ is a low potential zone, $.50 \le P < .75$ is a medium potential zone, and $P \ge .75$ is a high potential zone. Next, we selected the corresponding indicators for the socio-economic factors and collected the data to construct the screening layer. The data source was usually the official statistical yearbook. Finally, the four layers above were overlaid. Considering that in AHS, agricultural species and germplasm must be typical, unique, and representative. In the final identification, we required that only areas with high potential distribution of germplasm could become potential areas of AHS and the three socio-economic factors were indispensable. The regions that met the above requirements were potential areas for AHS based on agro-biodiversity.

2.2 | The case study

As one of the birthplaces of the world's agricultural civilization, China has an inherent advantage in discovering and preserving AHS. As of March 2023, China has 18 GIAHS, and 138 NIAHS have been selected. There are a large number of food germplasms originated from China, such as tea. The remains of an artificial tea plantation in Yuyao, Zhejiang province, dates back more than 6,000 years (Zhang, Rong, et al., 2018). Tea is typical and representative of traditional agricultural systems in China, with 3 of the 5 Tea-GIAHS (the GIAHS system with tea germplasm resources as the main object of cultivation) and 16 Tea-NIAHS of the 138 selected China-NIAHS. Today tea, along with cocoa and coffee, is one of the world's top three beverages and occupies an important place in the human diet. Therefore, this study used Chinese traditional tea germplasm resources as an example to identify the potential areas of Chinese Tea-AHS through the above-mentioned method (Figure 1). It aimed to provide technical support and methodological reference for the subsequent identification of global agricultural germplasm resource diversity.

2.2.1 | Identify potential areas by tea germplasm resources

Tea germplasm resources are a core element of agro-biodiversity in Tea-AHS. Therefore, the growth distribution of traditional tea germplasm resources is the priority factor for identifying their potential areas. In this paper, we constructed a distribution model of tea germplasm based on Maxent, whose special characteristic was that it made

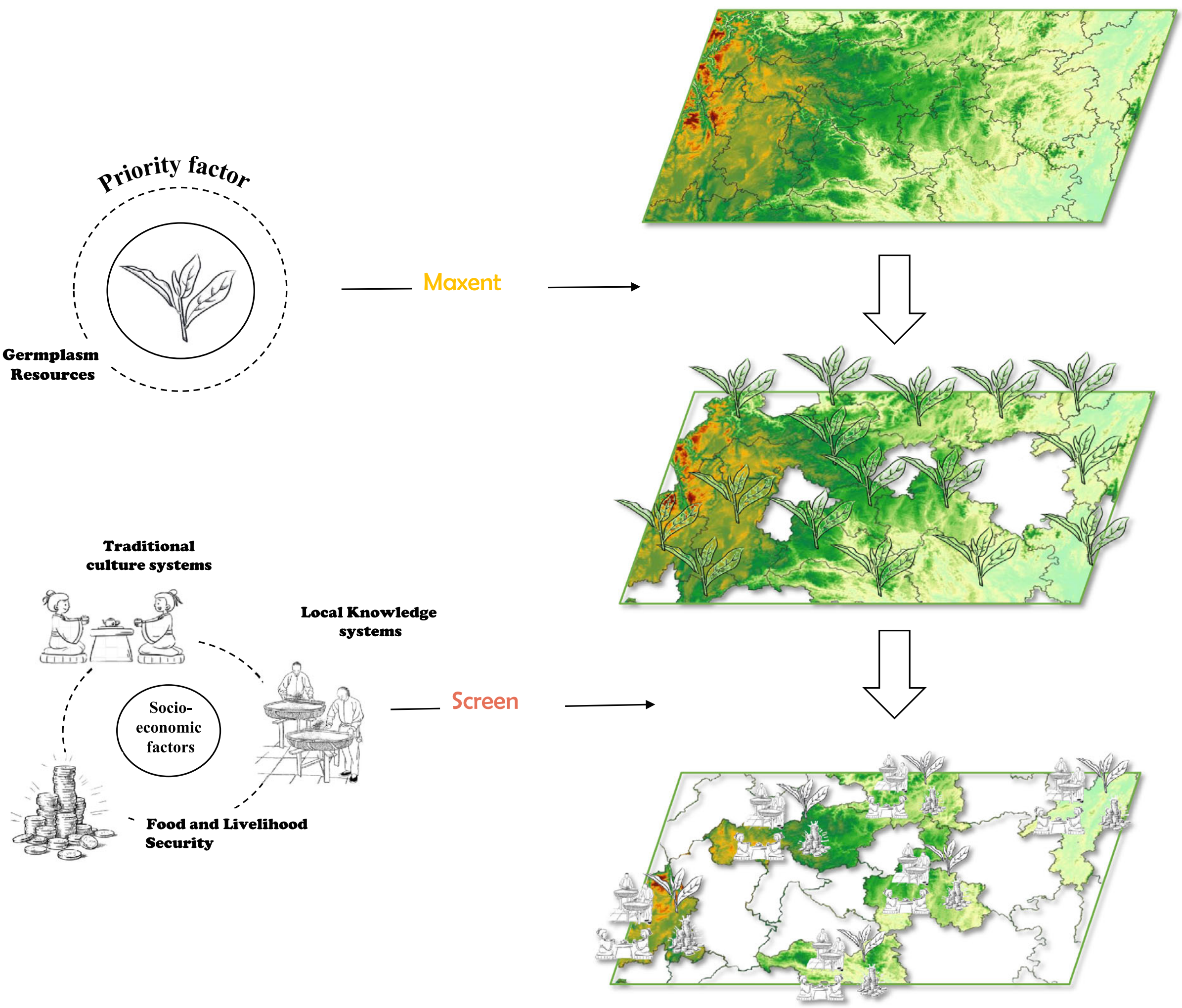

FIGURE 1 Schematic diagram of the process of identifying potential areas of agricultural heritage systems (AHS) based on agro-biodiversity. This study first used Maxent to screen the regions where traditional germplasm resources are located and then constructed layers of the socio-economics factors included farmers' livelihoods, local knowledge, and traditional culture, respectively, to further obtain the potential areas.

no subjective assumptions about the unknown while satisfying the input data as far as possible (i.e., the conditional entropy is maximum). The above process can also be described by the following equation.

$$
\begin{aligned}
\max H(Y|X) &= \sum_{X=x} p(x)(H(Y|X=x)) \\
&= \sum_{X=x} p(x)\left(-\sum_{Y=y} p(y|X=x)\log p(y|X=x)\right) \\
&= -\sum_{X=x}\sum_{Y=y} p(x)p(y|X=x)\log p(y|X=x) \\
&= -\sum_{x}\sum_{y} p(x)p(y|x)logp(y|x),
\end{aligned}
$$

$$
\text{s.t.} \sum_{x,y}\widehat{P}(x,y)f(x,y) = \sum_{x,y}\widehat{P}(x)P(y|x)f(x,y),
$$

where $H(Y|X)$ denotes the conditional entropy of the model; X represents the environmental information of a location; Y represents the distribution of tea germplasm resource at that location; and x and y are the specific values of the input environmental information and germplasm resource distribution, respectively. $P(x)$ is the prior information, and $P(y|x)$ denotes the posterior probability that the germplasm resource distribution is y in the case that the environmental information is x.

The constraint, $f(x, y)$ is an artificially defined characteristic function that accounts for the true state of the observed data and is defined as follows.

$$
f(x,y) = \begin{cases} 1, \ if \ (x,y) \in Dataset \\ 0, \ \text{else} \end{cases}
$$

With the help of this characteristic function and the empirical distribution $\widehat{P}(x,y)$ of events (X, Y) obtained from the observed data, it is possible to calculate the expectation $\sum_{x,y}\widehat{P}(x,y)f(x,y)$ of the occurrence of event (x, y) given the current observed data. In addition, according to the Bayesian formula, the occurrence expectation of event (x, y) can also be calculated from the empirical distribution $\widehat{P}(x)$ of the environmental variable X in the observed data, that is, $\sum_{x,y}\widehat{P}(x)P(y|x)f(x,y)$. By requiring the same expectation of event occurrence for both calculations, the model is able to meet the requirements of the actual data observations (Phillips et al., 2017; Phillips & Dudík, 2008).

The documented origins of tea germplasm resources were the model training samples for this study (Figure 2). The data sources used in the experiment were different, and Maxent required all environmental variables to have the same coordinate system, boundary, and resolution. Therefore, we used the projection conversion tools, extract tools, and resampling tools in ArcGIS to process them separately as 1 km × 1 km raster layers. For some of the point distribution data layers, we selected the optimal interpolation method using Automap to achieve a uniform distribution over the study area. The proportion of training set and test set data was 75% and 25%, respectively, and the range of raster values (i.e., suitability score) was [0, 1]. The Receiver Operating Characteristic (ROC) curve is applied to test the accuracy of Maxent's predicted distribution results, and the area under the curve is the AUC value. An AUC value greater than 0.8 is generally considered that the model is trustworthy. Maxent's open-source attributes allow for easy roll-out for subsequent worldwide AHS identification, which is why we ultimately chose it (Phillips & Dudík, 2008; Yang et al., 2022; Zhang, Yao, et al., 2018).

In order to determine the potential distribution of tea germplasm in China, the environmental variables that affected their growth needed to be clarified. By counting the environmental variables involved in the existing literature, the study collected a total of 67 environmental variables in three categories of resource endowment: climate, soil, and topography. It had been suggested that multicollinearity among environmental variables could interfere with the results during model prediction and screening of environmental variables was necessary before formal prediction (Dormann et al., 2013; Sillero & Barbosa, 2021). We combined the factors influencing tea growth from literature research, the correlation coefficient matrix between environmental variables, and Maxent's preliminary simulation results and finally utilized 34 environmental variables for simulation by considering the contribution value of each variable. The selected environmental variables are detailed in Table 2.

2.2.2 | Screened by socio-economic factors

The socio-economic factors food and livelihood security, local knowledge, and traditional culture also need to be considered in the identification of AHS. We set the identification unit at the county level, which is also the smallest unit for the conservation and management of China's AHS. There were 2,843 county-level administrative regions in China as of December 2021, and it was fairly detailed for a China scale model. It is worth clarifying that the model identifies potential AHS based on agro-biodiversity and should encompass all areas with potential. This means the potential areas only need to meet the minimum criteria for each socio-economic factor it has. For example, the

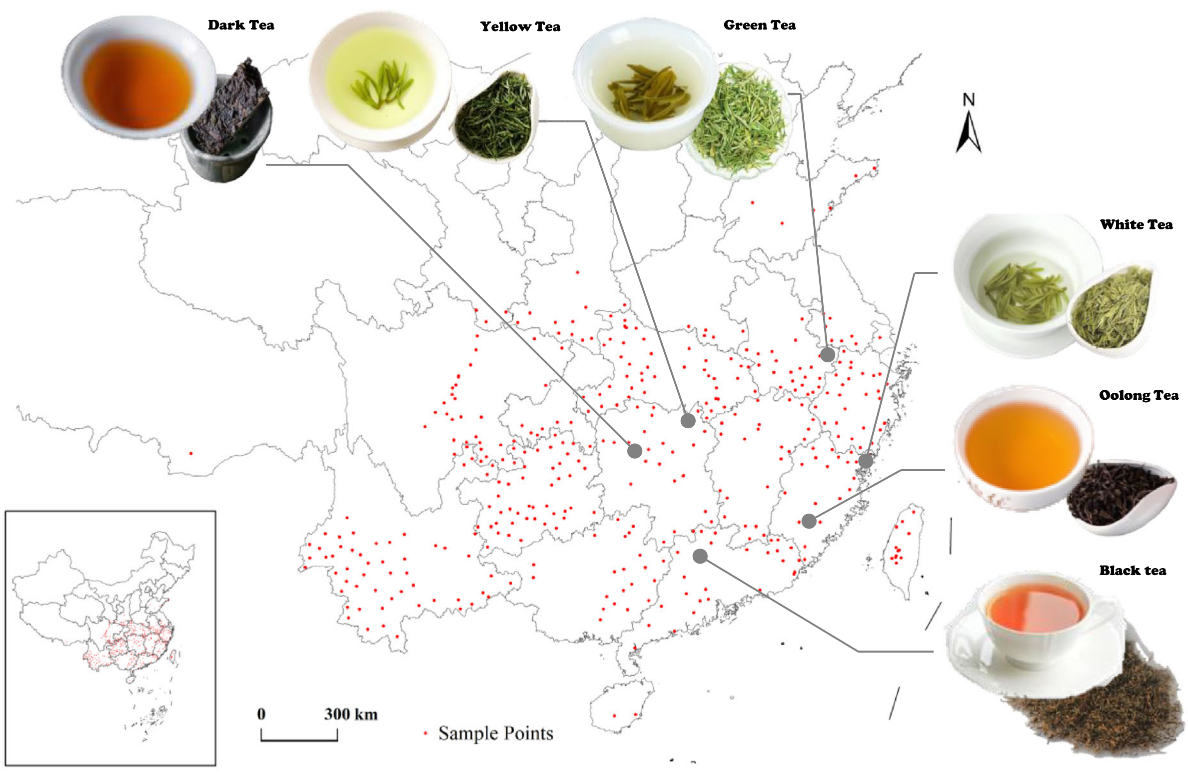

FIGURE 2 Distribution map of sample points ($N = 489$) of traditional tea origins in China. These sample points were used in Maxent to train the model to get the potential distribution areas of tea germplasm resources.

TABLE 2 Selected environmental variables used in the Maxent model after multicollinearity test to get the potential distribution areas of tea germplasm resources.

Climate variables			
Number of days with 0°C cumulative temperature	Temperature seasonality	Precipitation seasonality	Dryness
Number of days with 18°C cumulative temperature	Isothermality	Precipitation of driest quarter	Precipitation of wettest quarter
Soil variables			
Soil type	Gravel content[a]	Topsoil base saturation	Subsoil organic carbon
Drainage class	Topsoil clay fraction	Topsoil reference bulk Density	Total exchangeable bases[a]
Reference soil depth	Silt fraction[a]	Gypsum[a]	
Available water storage capacity	Subsoil cation exchange capacity (clay)	Sodicity (exchangeable sodium percentage)[a]	
Sand fraction[a]	Cation exchange capacity (soil)[a]	Topsoil calcium carbonate	
Topographical variables			
Digital elevation model	Type of landform		

[a]Two layers: upper soil (0–30 cm) and lower soil (30–100 cm).

statistical unit only needs to have one tea-related traditional technology to obtain the score for this indicator, and there is no requirement for a specific amount. This differs from the logic of subsequent more detailed protection policies such as the granting of GIAHS, which goes a step further in comparing the protection priorities and protection values of the many potential AHS.

Agricultural heritage emphasizes the coexistence and sustainable development of people and the environment, and its conservation and utilization cannot be separated from the most basic actor, the farmer (Yang et al., 2019). In traditional tea farming systems, tea production is not only a measure of a farmer's self-sufficiency but also an important guarantee of subsistence and market exchange. Therefore, this study constructed a county-level tea production distribution map in China to measure the contribution of the tea industry to the food and livelihood security of local farming households.

Local knowledge systems are another central element in the conservation of AHS. Specific agricultural systems and landscapes have been created, shaped, and maintained by generations of farmers using methods appropriate to local conditions based on different natural resources (Antonelli, 2023). These ingenious agricultural systems are based on local knowledge and experience, reflecting human evolution, the diversity of knowledge, and a profound relationship with nature (Fletcher et al., 2021). According to the growth process, traditional knowledge related to tea can be classified into five categories: variety selection, planting methods, harvesting techniques, tea management, and tea utilization. The existence of tea-related traditional knowledge is an important criterion in the Tea-AHS identification process, and we constructed a region map of documented tea traditional knowledge in China.

For each agricultural heritage, the unique varieties of agriculture, livestock, and fishery and the traditional knowledge and technology that go with them have their own specific cultural connotations. This constitutes the "cultural capital" that is exclusively owned by the community, and it is the value system and social organization that distinguishes it from other communities. In the history of tea drinking, China has gradually formed its own tea culture. It includes tea etiquette, tea spirit, tea couplet, tea book, tea opera, tea poetry, tea painting, tea science, tea stories, tea art, and even tea ancestor ceremony. The existence of a tea-related culture or a tea culture-supported community is also one of the important elements in the identification of potential Tea-AHS, and we constructed a geographical map of tea culture in China at this stage accordingly.

In summary, regarding the socio-economic factors, based on the annual tea yield α, the quantity of local tea knowledge β and the quantity of traditional tea culture γ, a unified indicator score function F can be established as follows, where e can represent any one of the three variables above.

$$F_{(\alpha,\beta,\gamma)} = \begin{cases} 1, & \text{if } e \neq 0 \\ 0, & \text{else} \end{cases},$$

where $e \in \{\alpha,\beta,\gamma\}$

2.2.3 | Identify potential areas of Tea-AHS

Potential areas for Tea-AHS were identified by combining the above suitability scores for the growth and distribution of traditional tea germplasm resources and index scores of the socio-economic factors. The statistical unit of socio-economic factors was the county level, and the unit of identification of the potential distribution map of tea germplasm was 1 km × 1 km. Due to this discrepancy, identification unit of 1 km × 1 km needed to be converted to county in the overlay. There were many conversion methods. However, unlike previous cases where the average value was usually taken, heritage sites protected unique systems, and we were therefore more concerned with extreme values. The maximum raster value was identified as the suitability score of tea germplasm for the county. Hence, the tea germplasm resource suitability score $D(m)$ for each statistical unit can be expressed as

$$D(m) = \max\{p(y_i|x_i)|(x_i, y_i) \in A_m\},$$

where m is the individual county unit; A_m is the range of the county; and $p(y_i|x_i)$ is the suitability of tea germplasm at any point in the county unit.

So far, the score $I(m)$ for each statistical unit becoming a potential area for China's Tea-AHS can be expressed as

$$I(m) = D(m) + F_\alpha(\mathrm{m}) + F_\beta(\mathrm{m}) + F_\gamma(\mathrm{m}).$$

Considering that in the AHS, agricultural species and germplasm must be typical, unique, and representative, we required that only areas with high potential distributions of tea germplasm would be identified as potential areas of Tea-AHS in the final identification, that is,

$$D(m) \geq 0.75.$$

The three socio-economic factors, food and livelihood security, local knowledge systems, and traditional cultures systems, were indispensable. As a result, the conditions that needed to be met for the potential areas of Tea-AHS in China were as follows:

$$I(m) \geq 3.75.$$

2.2.4 | Data

The sample data of the origin of tea germplasm in China was obtained from literature, local flora, Global Biodiversity Information Facility (https://www.gbif.org/), and Chinese Crop Germplasm Resources Information System (https://cgris.net/). A total of 489 tea germplasm origin samples were collected by removing invalid and duplicate data. A total of 67 environmental variables were collected in this study from the World Climate Database (http://www.worldclim.org/), National Meteorological Science Data Centre (http://data.cma.cn/), the Harmonized World Soil Database version 1.2, and the Resource and Environmental Science and Data Center (https://www.resdc.cn/). The socio-economic database was sourced from the 2020 Statistical Yearbook of China's 333 prefectural-level regions, national, provincial, and municipal intangible cultural heritage lists and folk books, among others. The deadline for data collection was October 2022.

3 | RESULTS

3.1 | Potential areas of traditional tea germplasm resources

The AUC values of the training set and the test set of the model were 0.921 and 0.886, respectively, which indicated that this Maxent model had a good prediction effect on the growth distribution of traditional tea germplasm and the model was reliable. In order to verify again, we conducted regional statistics in ArcGIS of the 16 existing Tea-AHS located counties (including GIAHS and NIAHS) with the probability distribution obtained from the model. The simulated suitability scores for all systems lay in the high potential region ($P > .75$), which could also demonstrate the strong reliability of the model's prediction results (Table 3).

Figure 3a shows the potential distribution of traditional tea germplasm obtained from the Maxent. The areas with high potential were concentrated in southwest China and Taiwan, with an overall irregular and fragmented distribution. The areas of medium potential were the most extensive, basically covering the whole southern region of China. The areas of low potential were mainly distributed in the neighboring areas of the medium. We conducted geographical statistics on the results, and three provinces, Guizhou, Yunnan, and Sichuan, were the regions with high potential distribution ($P \geq .75$) of tea germplasm, among which Guizhou had the highest areas. Hubei, Chongqing, and Anhui also had high potential and medium potential areas ($.50 \leq P < .75$). Hong Kong and Macao had a small number of high potential areas, and Taiwan had many high and medium potential areas.

3.2 | Results of socio-economic factors screening

A total of 847 county-level units in China produced more than 2.78 million tons of tea in 2019, and Figure 3b illustrates these regions. Almost all of them were concentrated in the south. Anxi County in Fujian Province had the highest annual tea production of 73,428 tons, followed by Anhua County in Hunan (72,919 tons) and Meitan County in Guizhou (58,645 tons). While there were also many regions that produced only a few tons of tea, such as Cixi City in Zhejiang, Figure 3c shows a total of 262 counties with traditional knowledge and technology of tea that we collected. Technologies are mainly based on the tea frying process, for example, Qi Hong, Xihu Longjing and Pu'er belong to the six major tea groups: green tea, oolong tea, black tea, dark tea, yellow tea, and white tea. In addition, there are Yulin tea bubble, tree-tea intercropping, and other traditional knowledge related to tea planting and drinking, as well as the techniques of a few folk foods with tea as a component.

We finally collected 382 counties with traditional tea culture such as tea opera, tea tao, tea songs, tea etiquette, tea customs, tea dances, and tea ceremony (Figure 3d). Most of these cultures were listed in the intangible cultural heritage, such as oil tea customs, Bai three step tea, and tea picking opera. Thus, their uniqueness, typicality, and the urgent need for protection and transmission can be illustrated.

3.3 | Potential areas of Tea-AHS

Combining the above four layers, the final analysis identified a total of 102 county-level potential areas of China's Tea-AHS (Figure 4). This

TABLE 3 Results of the suitability scores for the 16 existing counties hosting tea-based agricultural heritage systems (Tea-AHS) listed in the Globally Important Agricultural Heritage Systems (GIAHS) and National Important Agricultural Heritage Systems (NIAHS) in the Maxent model developed for this study.

Name	Location	NIAHS/GIAHS date	Suitability score *P*
Jasmine and Tea Culture System of Fuzhou City	Fuzhou City, Fujian	2013/2014	0.871213
Pu'er Traditional Tea Agrosystem	Pu'er City, Yunnan	2013/2012	0.999624
Zhejiang Hangzhou West Lake Longjing Tea Culture System	Hangzhou City, Zhangjiang	2014/-	0.978114
Anxi Tieguanyin Tea Culture System	Anxi City, Fujian	2014/2022	0.876230
Hubei Chibi Yangloudong Brick Tea Cultural System	Chibi City, Hubei	2014/-	0.908900
Guangdong Chaoan Phoenix Monocotyledon Tea Culture System	Chaoan District, Guangdong	2014/-	0.789168
Hubei Enshi Yulu Tea Culture System	Enshi City, Hubei	2015/-	0.975873
Ancient Tea Plantations and Tea Culture System in Mengku, Shuangjiang, Yunnan	Lahu-Va-Blang-Dai Autonomous County of Shuangjia, Yunan	2015/-	0.947749
Guizhou Huaxi Ancient Tea Tree and Tea Culture System	Huaxi District, Guizhou	2015/-	0.992248
Anhui Huangshan Taiping Monkey Kui Tea Culture System	Huangshan District, Anhui	2017/-	0.999274
Fujian Fuding White Tea Cultural System	Fuding City, Fujian	2017/-	0.862551
Sichuan Mingshan Mengdingshan Tea Culture System	Mingshan District, Sichuan	2017/-	0.950153
Jiangsu Wuzhong Biluochun Tea and Fruit Complex System	Wuzhong District, Jiangsu	2019/-	0.999998
Hunan Anhua Black Tea Cultural System	Anhua County, Hunan	2019/-	0.905711
Ancient Tea Plantation and Tea Culture System at Jinjinzhai, Baojing, Hunan	Baojing County, Hunan	2019/-	0.945940
Jiangxi Fuliang Tea Culture System	Fuliang County, Jiangxi	2021/-	0.853402

Note: All 16 existing Tea-AHS are located in high-potential areas, thus validating the reliability of the model.

included a total of 28 regions where 16 existing Tea-AHS were located (some AHS contain multiple counties). Among the remaining 74 counties, some of them had the same traditional knowledge, technology, and cultural system, and their geographical locations were close to each other, so they could be combined into one larger area for common protection. Finally, 54 potential AHS areas with tea germplasm resources were identified. All these areas were in the southern region, in 15 provinces, including Anhui, Fujian, and Guangdong. Over all these regions, 11 of 15 provinces already had protection policies such as Tea-GIAHS or Tea-NIAHS. The Guangxi and Henan provinces had five and one potential areas, respectively, but did not yet have a Tea-AHS as of July 2022, so related exploration and conservation work needs to be done urgently.

A probability density function was calculated for 54 potential areas, and the potential areas with *I* (*m*) scores greater than 3.95 but not yet listed in the GIAHS or NIAHS are displayed in Figure 4, totaling 19. These should be the top priorities of future exploration and conservation work on this topic. Figure 4 also shows the details of their suitability scores of tea germplasm, annual tea yield, local knowledge systems, and traditional culture systems. Among the existing AHS, Pu'er Traditional Tea Agrosystem has been supported by policies such as GIAHS and NIAHS. However, our study found that Zhenkang County, Yun County, Gengma Dai Wa Autonomous County, and Canyuan Wa Autonomous County in Lincang City are also rich in germplasm resources and culture of Pu'er tea. In the subsequent conservation process, these areas should be considered as an extension project of Pu'er Traditional Tea Agrosystem.

4 | DISCUSSION

The most distinctive feature of the AHS is that it is "alive." That is, although it was born in the past, it is still exists to this day. The current modern agriculture system, which is based on the consumption of large amounts of resources and energy, has some serious and unavoidable disadvantages and has led to a series of global ecological and environmental problems (Chen et al., 2017). In contrast, traditional agricultural systems in some areas have unique advantages in terms of adapting to climate change, providing ecosystem services and maintaining genetic diversity (Antonelli, 2023; FAO, 2021; Fletcher et al., 2021). Humanity is beginning to recognize the importance of conserving these important germplasm resources and

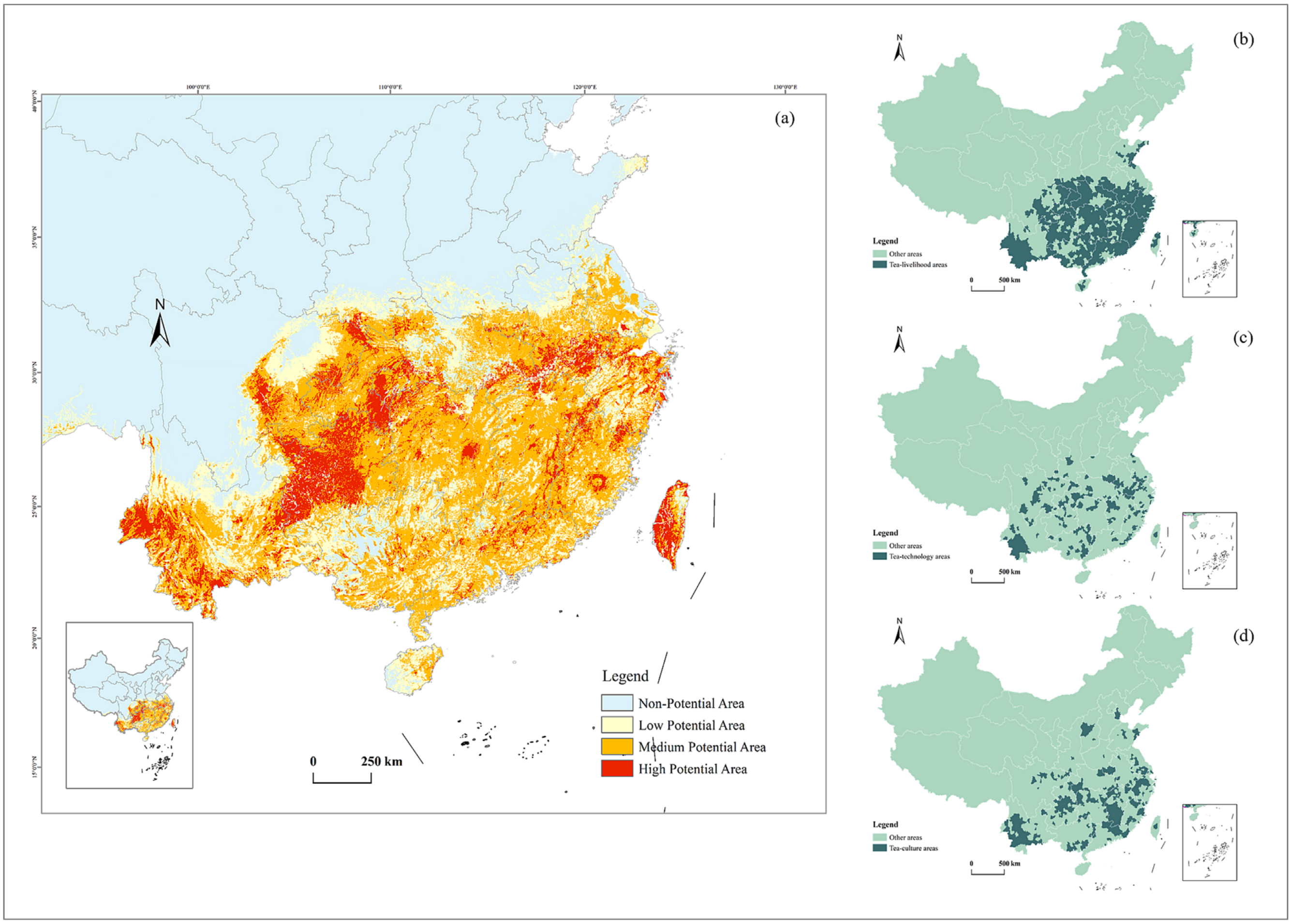

FIGURE 3 Layers of factors for identifying potential tea-based agricultural heritage systems (Tea-AHS). (a) Potential distribution of traditional tea germplasm. The areas of high potential were concentrated in southwest China and Taiwan, with an overall irregular and fragmented distribution. (b) Food and livelihood security. A total of 847 county-level units in China produced more than 2.78 million tons of tea in 2019. (c) Local knowledge systems. Total 262 counties with traditional knowledge and techniques of tea. (d) Traditional culture systems. Total of 382 counties with traditional tea culture, value systems, and social organizations.

indigenous knowledge. However, the AHS also face serious threats and vulnerabilities. In the context of modernization and urbanization, their future is threatened because the younger generation is less interested in maintaining traditional farming systems. In a survey of the Hani Rice Terrace in Honghe, Yunnan, 70.7% of respondents did not want to work in agriculture, and 88.7% did not want their next generation to continue working in agriculture (Zhang et al., 2015). Another significant impact of labor loss is the loss of germplasm, traditional knowledge technology, and associated culture. Studies in the Mengku Ancient Tea Garden in Shuangjiang, Yunnan, have shown that the older generation holds the traditional knowledge on the use of wild plant resources, and with their gradual passing away and many young people going out to make their lives, the transmission of these traditional germplasms and indigenous knowledge is facing a crisis (Ma et al., 2020).

Furthermore, modern techniques and measures have been inappropriately introduced into the traditional agricultural system in the pursuit of food production. For example, more and more landraces are being replaced by genetically homogeneous varieties; the woods in the original tree-tea intercropping are being cut down and converted into large areas of terrace tea. In the short term, this shift could increase the area planted with tea and thus increase production. But in the original tree-tea intercropping system, the tree plays ecological functions such as soil and water maintenance and nutrient cycling and maintains the biodiversity of the system, thereby ensuring the stability of the ecosystem. The change from intercropping to single terrace tea destroys the structure of the composite ecosystem, disrupts ecological functions, and reduces the resilience of food production. In the long term, this reduction in ecosystem function will in turn lead to increased use of fertilizers and pesticides by farmers, creating a vicious cycle that threatens the sustainability of agricultural production systems.

Before more germplasms and valuable knowledge inherent in traditional agriculture disappear, it is particularly urgent to identify agricultural heritage areas with traditional germplasm resources. However, few studies have focused on this issue. Therefore, the

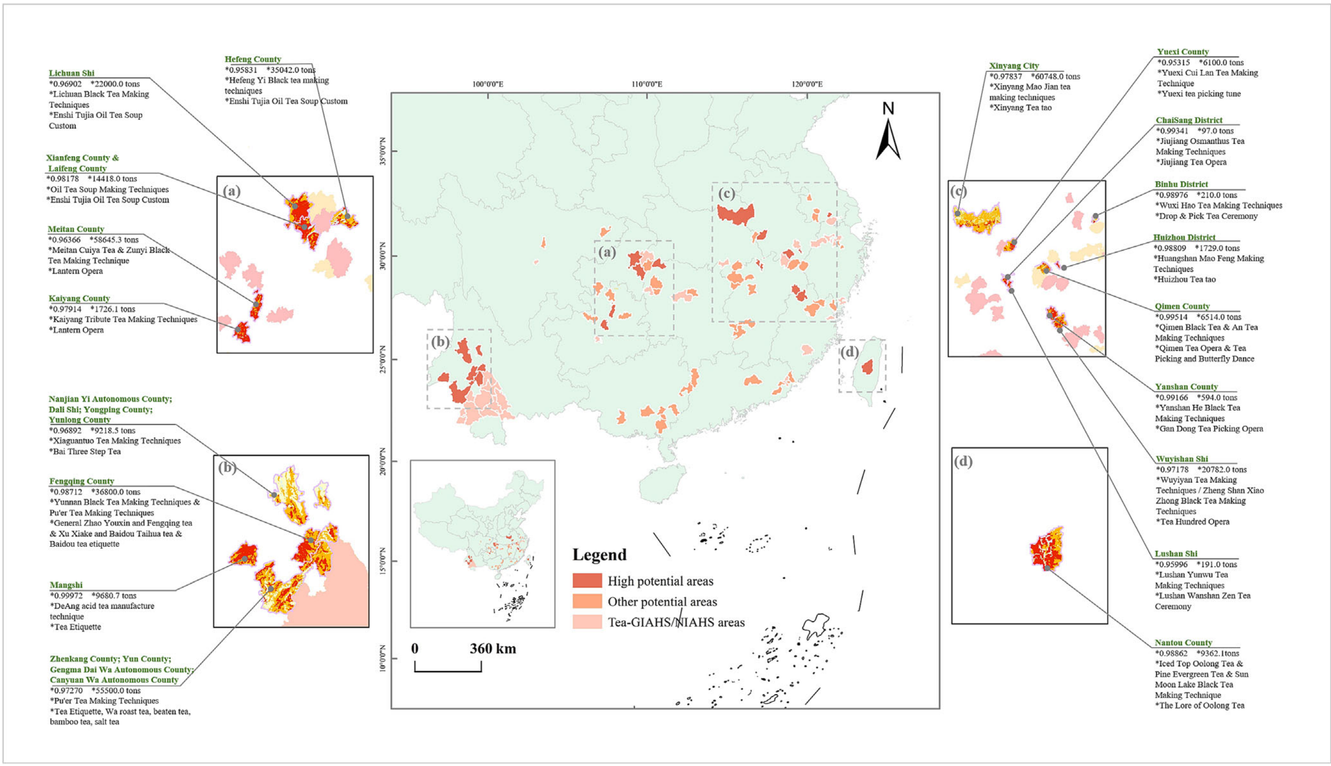

FIGURE 4 Results of the identification of potential areas of tea-based agricultural heritage systems (Tea-AHS) in China. Fifty-four potential areas of China's Tea-AHS were identified. High potential areas with $P \geq .95$ were marked in the figure. *Followed by suitability scores of traditional tea germplasm, annual tea yield, local knowledge, and traditional cultures for the region, respectively.

innovation of this study is that it provides the first method to identify potential areas of AHS based on agro-biodiversity. Taking Chinese tea germplasm as an example, we provided the first map of potential areas of Tea-AHS in China. In theory, the method is universally applicable to AHS where germplasm is the core of protection and can be extended to most crop species, as well as to any country in the world. However, there are several points to be considered. First, the input samples of this method should preferably be germplasm origins of perennial crops (e.g., tea, dates, olives, and prunes), which are relatively well documented, rather than annual crops such as rice and wheat. Second, the number of samples needed for the study is closely related to the size of the study area. More basic data are needed for global prediction, which requires not only the coordination of international organizations but also the active participation of countries around the world. Third, identification of AHS areas on a larger scale requires a balanced consideration of the general applicability of the selected socio-economic indicators in each country. In addition, traditional knowledge, technology, and related culture are usually transmitted and applied over a wide area, so the protection boundary needs to be determined when constructing associated layers.

At this stage, the conservation and management of AHS is mostly bounded by administrative divisions, so counties were chosen as the identification unit for this study. The potential areas of AHS could be further refined by combining with the land use pattern of each county, but due to the high demand of data, it was difficult to collect and analyze them one by one in this paper. When putting the findings of this study into practice, the map can be combined with local land use status and landscape features, facilitating field visits and enabling more detailed exploration and conservation of traditional germplasm resources in the future. While the use of administrative divisions as boundaries has the advantages of ease of management and clear ownership, it also tends to cause regional fragmentation of AHS. Locating the regional and watershed correlations of similar AHS and using natural boundaries as identification units is a direction worthy of future research.

At this stage, only a few types of AHS, such as mulberry-dyke & fish-pond and rice-fish, have attracted the attention of international scholars (Astudillo et al., 2015; Ren et al., 2018). However, pioneers around the world have also created a variety of AHS with organic links within production depending on natural conditions. Further preliminary studies are needed to prove the diversity of their germplasm resources, ecological effects, and material cycles. The organic combinations and clever design among the components of these systems are also likely to be very important for the sustainable development of our modern agriculture. Being "alive" means that it still exists, but it also means that it will continue to evolve. Conservation and utilization are not just a return to the past, but the preservation of the essence of traditional agricultural systems (germplasm resources, indigenous knowledge, traditional culture, etc.) and the integration of modern technologies, such as the Internet. Overall, identifying AHS is only the first step in their conservation and utilization. The establishment of dynamic conservation plans that help local people to obtain additional support for the transmission of germplasm resources, indigenous knowledge, preserving the diversity of genes, innovative fire, and practical techniques for modern eco-agriculture are the key subsequent steps.

AUTHOR CONTRIBUTIONS

Yunxiao Bai: Methodology; software; writing—original draft preparation; supervision; validation; writing—data curation. **Xiaoshuang Li**: Visualization; software; data collection. **Yuqing Feng**: Data interpretation; visualization. **Moucheng Liu**: Conceptualization; design of the research; reviewing and editing; funding acquisition. **Cheng Chen**: Conceptualization; reviewing and editing; validation.

ACKNOWLEDGMENT

This research was supported by the Beijing Innovation Consortium of Agriculture Research System (BAIC09-2023).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Bai, Y., Li, X., Feng, Y., Liu, M., & Chen, C. (2024). Preserving traditional systems: Identification of agricultural heritage areas based on agro-biodiversity. *Plants, People, Planet*, *6*(3), 670–682. https://doi.org/10.1002/ppp3.10479