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High-precision Ecological Protection Red Line Boundary Optimization for Fangshan District, Beijing, China

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In recent years, China's resource and environmental problems have become increasingly severe, and the pressure on resource constraints has continued to increase. The Chinese government has delineated constraints for spatial planning based on the ecosystem, that is, a "red line for ecological protection", which aims to "control the ecological space" and optimize the ecological environment. The optimized verification of this red line can improve the accuracy of its boundary, ensure habitat integrity, and provide data and methods supporting the protection of the ecosystem. In this study, the problems of verifying the boundary of the ecological protection red line include five major categories and 24 minor categories, such as accuracy problems, current situation problems, contradictions with planning, boundary consistency problems, and integrity problems. Taking Fangshan District, Beijing, China, as an example, based on the results of delineating the ecological protection red line in Fangshan District, we integrated geographical monitoring, land use surveys, high-resolution remote sensing images, small forestry classes, protected areas, road networks, water networks, and 14 types of multi-source data, such as architectural and planning data. On the basis of the idea of clustering, we granulated the types of plaques in the ecological protection red line into three categories, nature reserves, river wetlands, and other protection units, and we assessed multi-source data regarding the specific problems of various types of plaques in the ecological protection red line. We used an adaptive design, using the big data processing mode of red line plaque fragmentation, based on ArcGIS spatial data analysis and processing functions to optimize and verify the red line boundary. We obtained a mapping accuracy of 1:10000 for the ecological protection red line, which is a breakthrough in accuracy. This study provides a base map for ecological protection via the red line management, supervision, and comprehensive implementation of land and space planning. The research method is also applicable to research on optimizing the red line boundary for ecological protection in other regions of the country.

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1. Introduction

The ecological protection red line refers to an area that has special important ecological functions within an ecological space and must be strictly protected. It is the bottom line and lifeline for ensuring and maintaining national ecological security.(1) The delineation of the ecological protection red line is a strategic requirement of China, and it is an important measure used to promote China's "five in one" strategic layout and the construction of an ecological civilization.(2) Many scholars have studied the delineation, landing, and management of the ecological protection red line across China. Other countries have also protected their ecological environments by delimiting ecological protection red line areas. For example, Japan has designated 60% of its land area as ecological land.(3) The development of China's ecological protection red line used 2011 as the baseline and was divided into the budding and rapid development periods.(4) In 2011, the State Council first proposed the strategy of protecting the ecological environment by delimiting the ecological protection red line, which embodies China's determination to implement the most stringent ecological environmental protection strategy in history.(5) In 2015, the Chinese government launched the Delimitation and Protection of the Ecological Protection Red Line policy, the purpose of which is to integrate all protected areas into a unified and strict management system.(6–8)

Regarding the identification and delineation of the ecological protection red line, different scholars have studied different areas and landforms. Wu used a large-scale regional division method to study southwest China and divided the region into protected, construction, conflicted, and low-pressure areas.(6) Xu *et al.* used three ecological models (InVEST, RUSLE, and CASA) and five key indicators to establish a consistent framework and standards for the ecological protection red line; additionally, they identified the ecological red line in the Yangtze River Economic Belt.(10) The same group studied a blueprint of China's ecological protection red line and key indicators for measuring the line, spatial analysis and classification methods, and protection policies.(11) Wang *et al.* evaluated the coastal and terrestrial ecosystems in Liaoning and established protection and environmental pressure indicators to identify the ecological red line in coastal areas of Liaoning Province, China.(12) Zhang *et al.* performed Geographical Information System–based multi-criteria decision analysis (GIS-MCDA) with an indicator system, indicator weights, and coverage rules to measure the degree of urban ecological vulnerability on the GIS platform.(13) Zhang *et al.* studied the conflicts among three land management red lines (urban growth boundary, ecological protection red line, and basic farmland protection area) using various statistical analysis methods, including spatial autocorrelation, imaging gradients, and landscape pattern analysis, and researched the driving forces of these conflicts.(14) Using Xiamen Bay as a research area, Hu *et al.* studied the method of delineating the red line of coastal marine ecological protection and proposed a comprehensive framework to establish an index system (including 26 indexes) for delineating the red line region.(15)

Gao *et al.* summarized the theory and practice of delineating the ecological protection red line in China and proposed countermeasures and approaches to address the problems and challenges faced by the ecological protection red line in the processes of delineation, management, and implementation.[16] Wang *et al.* assessed the ecological problems in the Qilian Mountains and made proposals to promote the implementation of the ecological protection red line by accelerating comprehensive scientific investigations, improving and implementing the ecological compensation mechanism, and exploring a coordinated development model oriented by a positive list.[17] Zou *et al.* conducted a comparative analysis of the concept of the ecological protection red line and the concept of red lines for other elements, and they proposed management ideas and methods that can be used in the delineation of the ecological protection red line to promote its final landing.[18] The progress and shortcomings of the relevant theories and research methods related to the ecological red line have been assessed. In view of the shortcomings of the delineation method for the ecological protection red line, we propose a new delineation method based on ecological security pattern theory, and we verify the operability of the method on a municipal scale.[19]

In the field of identifying city and urban agglomeration, relevant studies have been conducted on the ecological protection red line.[20–22] Different regions have been studied, such as Changchun,[22] Bohai Rim,[23] Qiqihar,[24] and Songnen. Li *et al.*[25] showed that the regional economic development and the economic effects generated by export enterprises have a negative impact on animals living in the red line area; however, a positive impact has been noted in some cases. The Yangtze River is the longest river in China, and the Yangtze River Economic Belt has an impact on the Chinese economy. Because of its importance, research has been performed on the Yangtze River's ecological protection red line.

Research on the ecological protection red line has mostly focused on the delineation method, theoretical research, and management policy research of the line; there have been few studies on the accuracy problems, the boundary optimization check, and the landing of the ecological protection red line boundary. This study was based on the ArcGIS platform and used high-resolution remote sensing image data and geographic and national condition monitoring and other multi-source basic data. Additionally, on the basis of the grading and classification of the ecological protection red line boundary check optimization in Beijing, the boundary accuracy of the ecological protection data itself is optimized. Figure 1 provides the research workflow used to generate the most basic data baseline map for the ecological protection red line.

2. Study Area

Fangshan District is located in the southwestern part of Beijing, China (39°30'–39°55'N, 115°25'–116°15'E). The southwest gateway of Beijing, with an area of approximately 2019 km^2, has a high elevation in the mountainous northwest (two-thirds of the total area) and a low elevation in the plains in the southeast. Fangshan District is an ecological barrier area with a superior ecological environment including Fangshan Geological Park, the oldest primary secondary forest in North China National Forest Park; the largest karst cave group in northern China; Shihua Cave; Yinhu Cave; and the Shidu Scenic Area. Yongding River passes through the urban area, forming a green spatial structure in which the mountains and rivers are intertwined. Fangshan District has rich biodiversity, a complex natural environment, a complex ecological structure, and a variety of geological landforms. The height difference between the

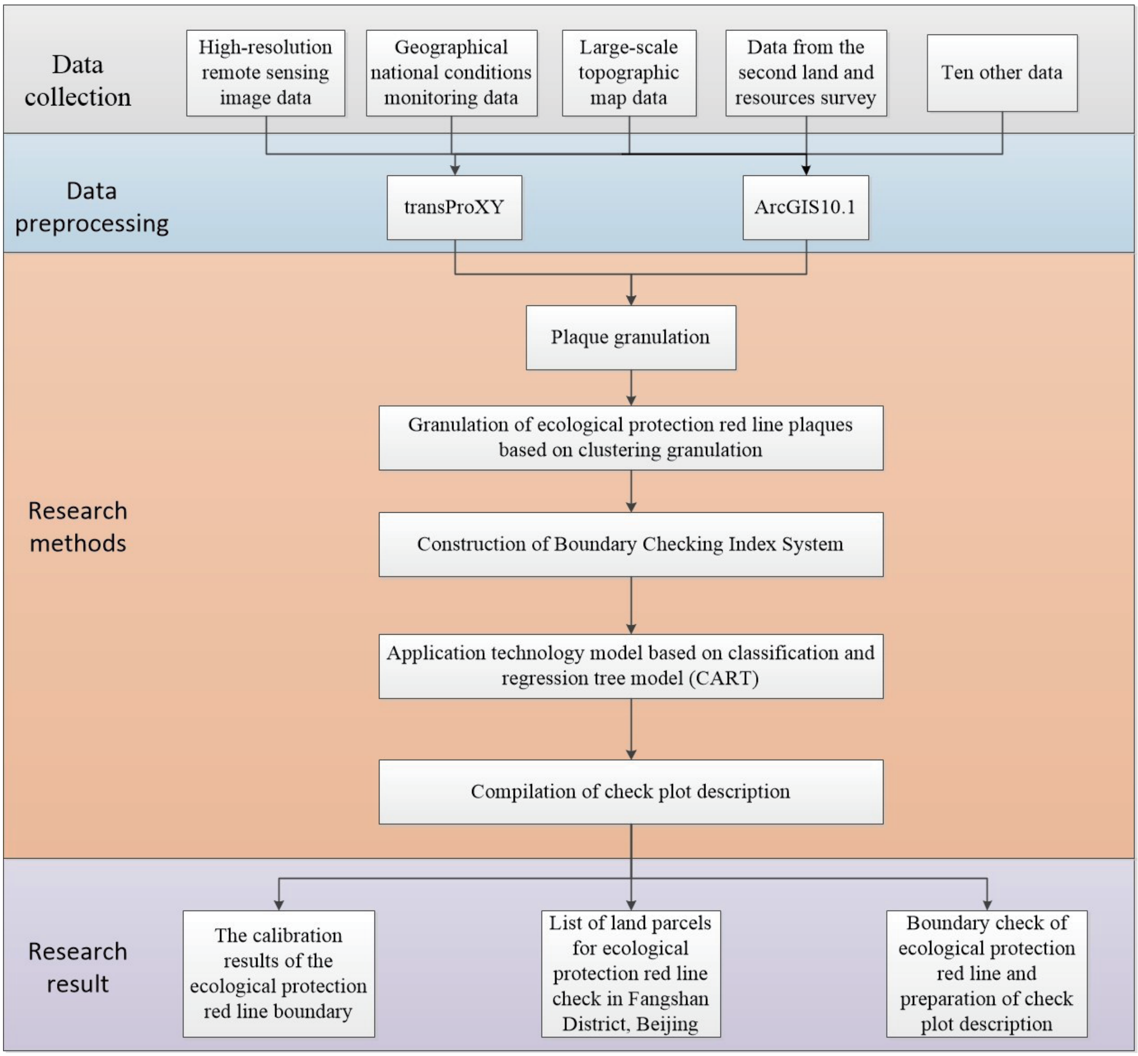


Fig. 1. (Color online) Workflow of ecological protection red line boundary optimization check.

mountainous areas and plains is large, resulting in a large variation in climate. The study area is shown in Fig. 2.

The area of the Fangshan ecological protection red line is approximately 627.13 km^2, and the perimeter is approximately 3480.28 km, accounting for 14.62% of the total area of Beijing's ecological protection red line and 31.43% of the area of Fangshan District. It mainly includes the mountainous areas in the northwest and the areas along the Juma River, Yongding River, and the South-to-North Water Transfer Project. These areas include important river wetlands and water and soil conservation areas (e.g., Juma River, Yongding River, and South-to-North Water Diversion, with an area approximately 34.58 km^2), and areas responsible for maintaining biodiversity and other important ecological functions (China Fangshan Geological Park, Shidu Scenic Area, and Shihuadong Landscape Scenic Area, with an area of approximately 592.55 km^2). The red line of the ecological protection boundary in Fangshan District is extremely irregular and has jagged borders, and the habitat integrity is poor.

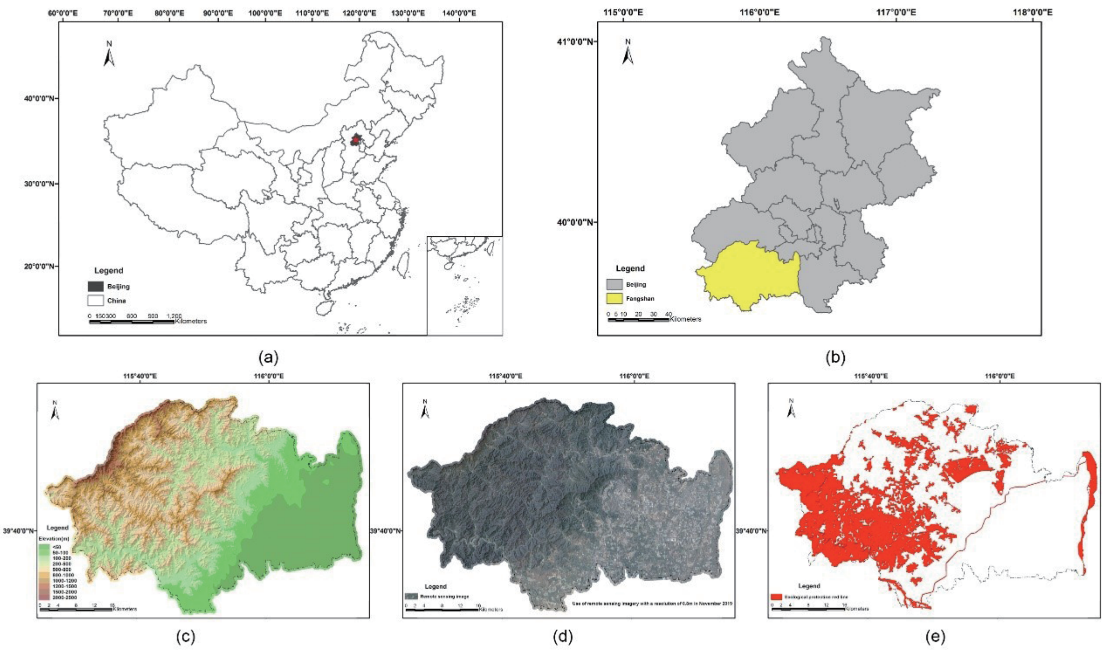


Fig. 2. (Color online) Overview of ecological protection red line in the study area: (a) China, (b) Beijing, (c) Fangshan, (d) Fangshan remote sensing image, (e) Fangshan ecological protection red line (before checking).

3. Materials and Methods

3.1 Integration and preprocessing of multi-source data

Checking the boundary of the ecological protection red line is a labor-intensive task with high complexity and strict requirements. According to the requirements of China and Beijing, when changing the ecological protection red line, sufficient proof must be provided to justify each change. The ecological protection red line involves different ecological elements, such as mountains, forests, fields, lakes, and grasses, most of which involve protection units, such as nature reserves, forest parks, and scenic spots. However, other elements may not include protection units. The red line patch elements must be supported by reference data with clear geographic boundaries when they are checked. Therefore, the timely and comprehensive collection of multi-source data is the basis for verifying the ecological protection red line boundary. At the same time, owing to differences in data format, mathematical projection basis, and the reliability of data type, it is necessary to carry out data analysis and unify the reference basis.

The basic reference data of the ecological protection red line boundary check include high-resolution remote sensing image, geographic national condition monitoring, large-scale topographic map, and secondary land and resource survey data. This study combines the types of plots included in the Fangshan ecological protection red line and the reference data collected to meet the basic data requirements while additionally including data on nature reserves, various types of protection units, and single building data. Owing to the lack of data, these materials have provided strong support and protection in improving the efficiency of the work on verifying the ecological protection red line border, improving the accuracy of the results, and ensuring the accurate landing of the red line.

With the support of the Beijing Municipal Bureau of Ecology and Environment, the Beijing Academy of Environmental Sciences, and the Beijing Municipal Planning and Nature Commission groups of various districts, combined with the data already available, a total of 14 types of main reference data were collected as shown in Table 1. The analysis of the data and the processing of the multi-source data mainly involve the transformation and unification of the data coordinate system. According to the requirements of technical documents such as Guidelines for the Delineation of the Ecological Protection Red Line and Technical Regulations for Defining Standards of Ecological Protection Red Line Surveys, the coordinate system should adopt the 2000 National Geodetic Coordinate System (CGCS2000). The coordinate conversion in this study used transProXY software (http://transproxy.sourceforge.net/). This software can convert between the Beijing local coordinate system and the 2000 Chinese national local coordinate system, and the accuracy of coordinate conversion meets the requirements of this research. We converted the above 14 types of data using transProXY software and imported the data into ArcGIS 10.1 (https://www.arcgis.com/index.html). All data were successfully imported and processed.

3.2 Ecological protection red line plaques based on clustering granulation

The ecological protection red line itself has complex data, and this complexity is reflected in the complexity of data patches and data problems. The modeling of complex data is the basis of data analysis and utilization, and the modeling mainly includes classification, regression, clustering, and decision-making. In the processing and modeling of complex data, the cognitive mechanism plays an important role. A well-known cybernetic expert in the United States noted the problem of the granulation of fuzzy information. He summarized the human cognitive ability as granulation (the whole is decomposed into parts), the three main characteristics of organization (parts integrated into a whole), and cause and effect (causal association). Information granulation is a process of granulating complex data into information granules through a given granulation strategy.

The patches contained in the ecological protection red line data have a variety of descriptions and coexistence phenomena. One red line patch belongs to nature reserves and forest parks, as well as scenic spots, and the boundaries of the three data forms cross each other. To ensure the accuracy of the ecological protection red line boundary check and the integrity of the habitat, on the basis of the idea of data granulation, the plaque types within the ecological protection red line were granulated into three categories: nature reserves, river wetlands, and other protection units.

Table 1
Types and descriptions of multi-source data.

Serial number	Type of data	Description of data
1.	Various nature reserves in Beijing	21 nature reserves in Beijing with legal borders (including core areas, buffer zones, and experimental area boundaries).
2.	Various protected areas	Mainly include protection units with clear boundaries, such as forest parks, geological parks, scenic spots, wetland parks, world natural heritage sites, and drinking water sources.
3.	Ground cover	Reflects natural attributes or conditions of natural and artificial structures on surface of land, mainly including planted land, forest, and grass cover; housing construction, railways, and roads (road cover classifications other than railways are unified as roads, regardless of category or level); structures, artificially dug, deserted, and bare land; and water areas of eight first-class categories.
4.	Road network	Collected in the form of geographic entities. Data includes the types, grades, and locations of roads and reflects structural characteristics, traffic conditions, distribution density, and relationships with other elements of road network. Mainly includes railways, highways (national, provincial, county, rural, and special roads and connecting roads between highways), urban roads (main roads, expressways, branch roads, etc.), rural roads, and ramps.
5.	Stand-alone buildings	Permanent places with roof and surrounding walls that can protect against wind and rain for people to work, live, study, entertain, and store supplies. Have fixed foundations occupying land space and generally have height of 2.2 m or more. Data attributes mainly include information about districts and counties, nature of land, nature of building, area of building, and number of floors above ground.
6.	High-resolution remote sensing images	Latest city-wide image data with resolution of 1 m. This study uses images from third quarter of 2019.
7.	Forestry resources survey subclass data	Latest forestry resources survey results provided by Beijing Municipal Bureau of Landscaping and Greening.
8.	Planted commercial forest	Data with attribute "artificial commercial forest" extracted from forestry resource survey subclass data.
9.	Land resources survey data	Including secondary tone data, land change survey data.
10.	Large-scale topographic map	1:5000 topographic map of Beijing city, 1:2000 topographic map of plain area, 1:500 topographic map of central city area.
11.	River blue line	Newly approved river protection scope provided by planning or water affairs department, mainly includes five major rivers in Beijing (North Canal, Yongding River, Chaobai River, Wenyu River, and Luan River).
12.	Permanent protection of farmland delineation results	Latest approval data provided by planning department.
13.	Town development border	Latest approval data provided by planning department.
14.	Partition planning data	Latest approval data provided by planning department

3.3 Application technology model based on classification and regression tree (CART) model

To promote the ecological protection red line to be set and landed, with the service of Beijing's ecological civilization construction as the core and the service of national land spatial planning as the guide, this study combines the actual situation of the Beijing ecological protection red line, innovatively categorizes and classifies the content of the Beijing red line border check, and formulates a fine-grained classification index system for content in the Beijing ecological protection red line border check, which greatly facilitates the accurate placement and implementation of the Beijing red line to support the smooth development of ecological protection policies in Fangshan District.

By combining the high-resolution remote sensing image data, the monitoring data of geographic national conditions, nature reserve data, and other special materials, we analyzed the delineation results of the Fangshan ecological protection red line in ArcGIS. On the basis of meeting the national requirements and combining the actual situation of the ecological protection red line in Beijing, the types of red lines that must be optimized are summarized and further classified. In this study, the types of ecological protection red line patches in Beijing to be optimized were divided into five first-level categories and 24 second-level categories, which are shown in Table 2.

3.4 Construction of the boundary check index system

The comprehensive application of multi-source data integrates various data to absorb the characteristics of different data sources and then extracts better and richer information than that

Table 2
Hierarchical classification of ecological protection red line patches in Beijing.

Check type	Specific reason
Accuracy exceeded	Red lines cut boundaries of construction land (houses, roads, etc.)
	Overall shift of plaque position
	Boundary fine-tuning
	Unreasonable holes
	Topological issues (topological errors such as face overlaps, face stabs, and minimal faces)
Contradiction with status quo construction	Massive settlements within red line
	Red line contains high-grade roads (roads above provincial level)
	Railways included in red line
	Expressways in red line
	Main roads included in red line
	Red line conflicts with land use status
	Status quo construction unsuitable for inclusion in red line
Conflict with planning	Zoning planning
	Special planning
	Urban development boundary
	Permanent basic farmland
	Major planning and construction projects
Consistent with administrative boundaries	Data edge
	Supplement to boundary
Preserving habitat integrity	Connectivity adjustment
	Remove broken plaques
	Connect with natural boundaries
	Linking boundaries of various protected areas

available using single data. The analytical classification of feature data currently uses the classification regression tree (CART) model. In this study, a CART model for entity objects was developed. Each type of ecological protection red line plaque was taken as the research object. The data types used in the verification process were divided into two parts, Yes and No, where the left branch has the value "Yes" and the right branch has the value "No". The regression number model is as follows.

Suppose that X and Y are the input and output vectors, respectively, Y is a continuous variable, and D is the training dataset

$$D=\{(x_1,y_1),(x_2,y_2),(x_3,y_3)\ldots\ldots(x_N,y_N)\}. \tag{1}$$

A regression tree corresponds to a partition of the input space (i.e., eigenvalues) and the output values on the partitioned units. Assuming that the input space has been divided into M units, i.e., R_1, R_2, ..., R_M, and there is a fixed output value (cm) on each unit (R_m), the regression tree model can be expressed as

$$f(x)=\sum_{m=1}^{M}c_m I\ (x\in R_m). \tag{2}$$

By combining the characteristics of this ecological protection red line boundary check and the characteristics of Beijing's ecological protection red line, the mountain, forest, lake, and grass categories in the red line are divided into three types according to the functional unit: natural protection, river wetlands, and other protection units. The CART model used for the comprehensive application of multi-source data for each type is shown in Fig. 3.

3.5 Compilation of check plot description

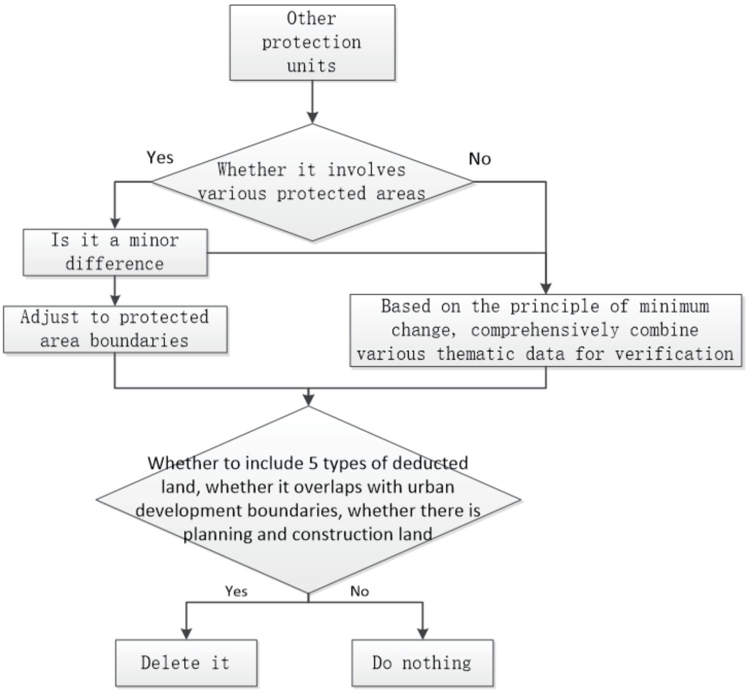
The boundary check of the ecological protection red line is a key step to ensure the accurate landing of the red line. This study is based on ArcGIS software, which has powerful spatial data analysis and spatial data processing capabilities, with each red line patch as the object. On the basis of the general principles of no reduction in area, no change in spatial layout, and no change in the nature of land use, according to the requirements of integrity, accurate landing, and orderly connection, the characteristics of the red line plaques and the type of verification required are analyzed; furthermore, with reference to the data, each change in the patch in the red line boundary check is recorded and explained in detail.

4. Results and Analysis

4.1 Calibration results of ecological protection red line boundary

During data processing, we followed the principles of maintaining habitat integrity, accurate landing, and orderly connection, allowing us to effectively process the data. Five types of problems were found in the ecological protection red line boundary check: accuracy problems,

Fig. 3. CART model for comprehensive application of multi-source data: (a) CART model of red line involving nature reserves. (b) CART model of red line involving river wetlands.

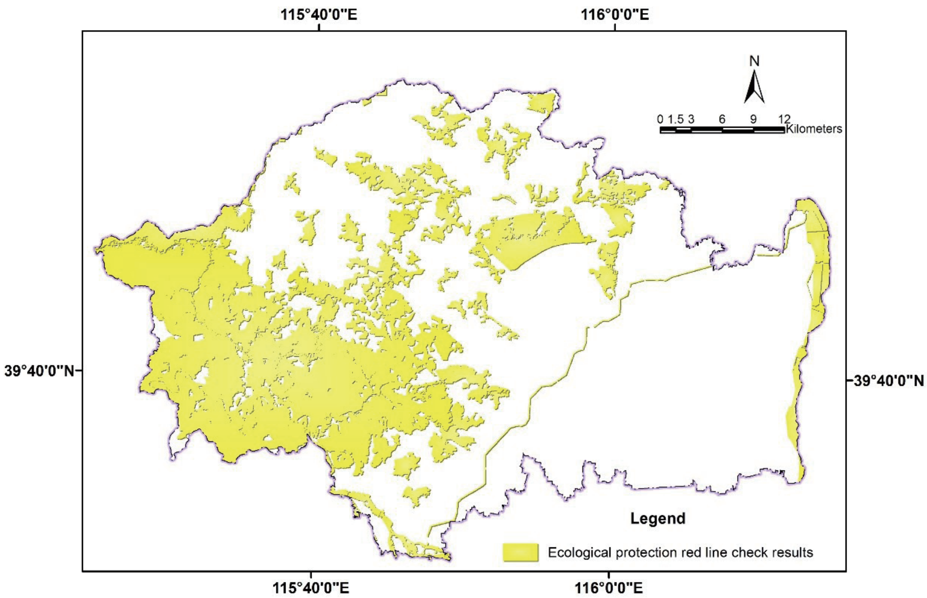


(c)

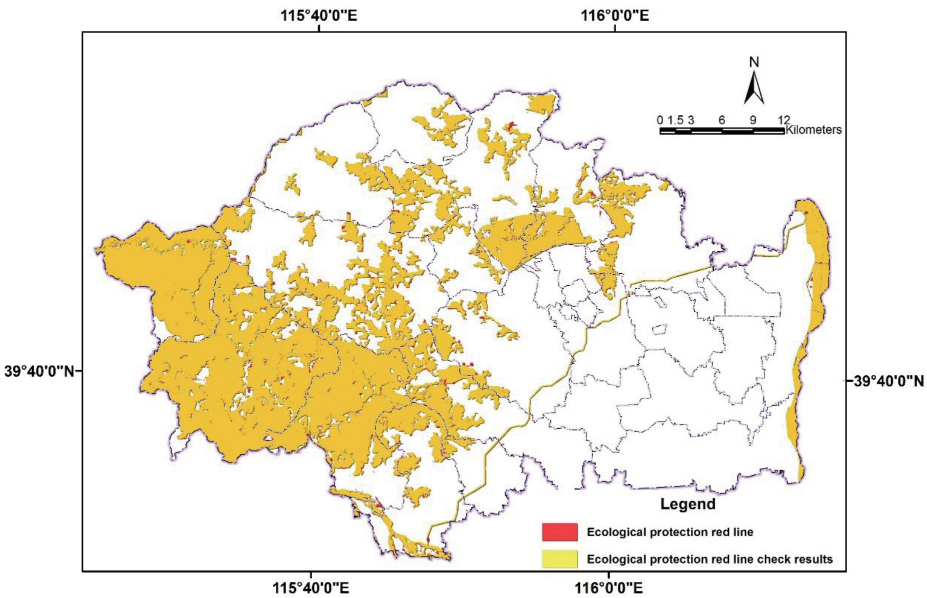
Fig. 3. (Continued) CART model for comprehensive application of multi-source data: (c) CART model of red line involving other protection units.

current situation issues, contradictions with planning, boundary consistency issues, and integrity issues. We optimized the verification model according to the plaque fragmentation of big data and dealt with the above problems. The red line distributions before and after the treatment are respectively shown in Figs. 4(a) and 4(b).

The plaques adjusted during the calibration process are divided into two types: "supplemented" and "reduced". The plaques that are added and reduced are overrun according to accuracy, contradiction with the current situation, contradiction with the planning, and consistency with the administrative boundary. The five complete categories of habitats are classified to explain the reason and basis of verification, involving a total of 11113 plaque adjustments. Before the check, the area encompassed by the red line was approximately 627.13 km^2, while after the check, it was approximately 630.13 km^2, an increase of approximately 3.00 km^2. There were four types of reduced plaques, those caused by habitat integrity, precision overrun, contradictions with planning, and current status construction, and there were 6107 reduced plaques, with a reduction in area of approximately 14.64 km^2. Supplemented plaques were related to maintaining habitat integrity, exceeding accuracy limits, remaining within administrative boundaries, and three other reasons, involving a total of 5006 plaque adjustments, with an increase in area of approximately 17.64 km^2.



(a)



(b)

Fig. 4. (Color online) (a) Results of the red line boundary check study of ecological protection in Fangshan District, Beijing before the check. (b) Results of the red line boundary check study of ecological protection in Fangshan District, Beijing after the check.

4.2 List of land parcels for ecological protection red line check in Fangshan District

Reduced land parcels: Among the 6107 plaque reductions, the habitat integrity category had approximately 191 plaques with an area of approximately 0.34 km^2, the exceeded accuracy category had approximately 5500 plaques with an area of approximately 12.09 km^2, and the planning contradiction category had approximately 115 plaques with an area of approximately 0.88 km^2. There were 301 contradictory constructions with an area of approximately 1.33 km^2. Figure 5 shows the increases and reductions of the plots of the Fangshan ecological protection red line area, and the statistics of plaques with an area greater than 0.01 km^2 are shown in Table 3.

Description of supplemented plots: Before and after checking the red line of ecological protection in Fangshan District, the red line was adjusted. There were three types of supplemented plots involving 5006 sites, with a total increase in area of 17.64 km^2. Among them, there were approximately 143 habitats with a total area of approximately 0.50 km^2, approximately 4821 sites in the over-accuracy category with an area of approximately 17.05 km^2, and 42 sites that were consistent with the administrative boundary with an area of approximately 0.09 km^2. Statistics of plaques with an area greater than 0.01 km^2 are shown in Table 4.

4.3 Boundary check of ecological protection red line and preparation of check plot description

Figures 5(a) and 5(b) show that, at the scale of 1:220000, the difference between the overall ecological protection red line in Fangshan District before and after the boundary check is not obvious. The areas of the added and deleted plots are greater than 0.01 km^2 and less than 0.2 km^2, respectively. Therefore, we used a chart comparing the map before and after the specific addition and deletion of borders to show the effect of using the ecological protection red line border verification workflow. We solved all five types of problems mentioned in Sect. 1.

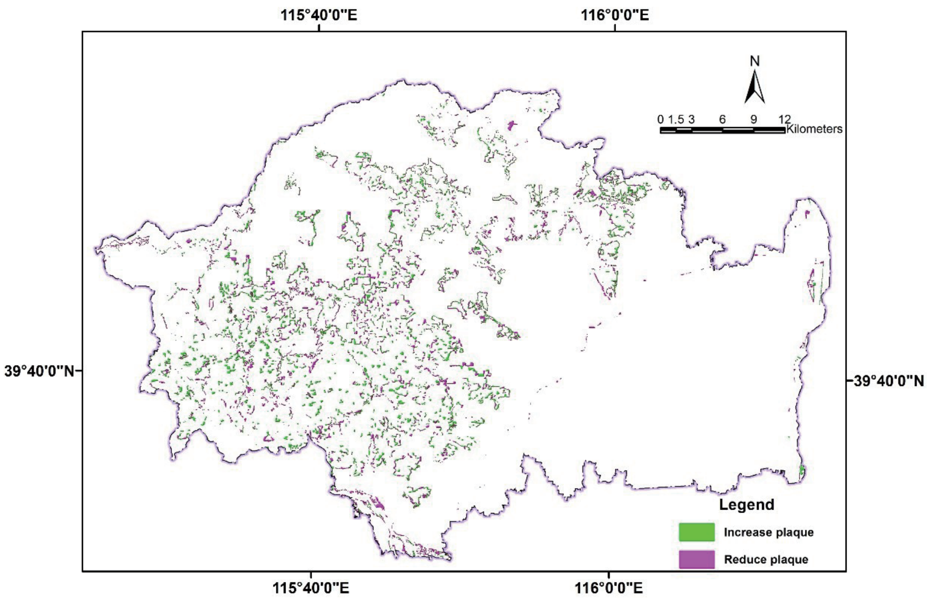


Fig. 5. (Color online) Increases and decreases of the red line check plots of Fangshan ecological protection red line area.

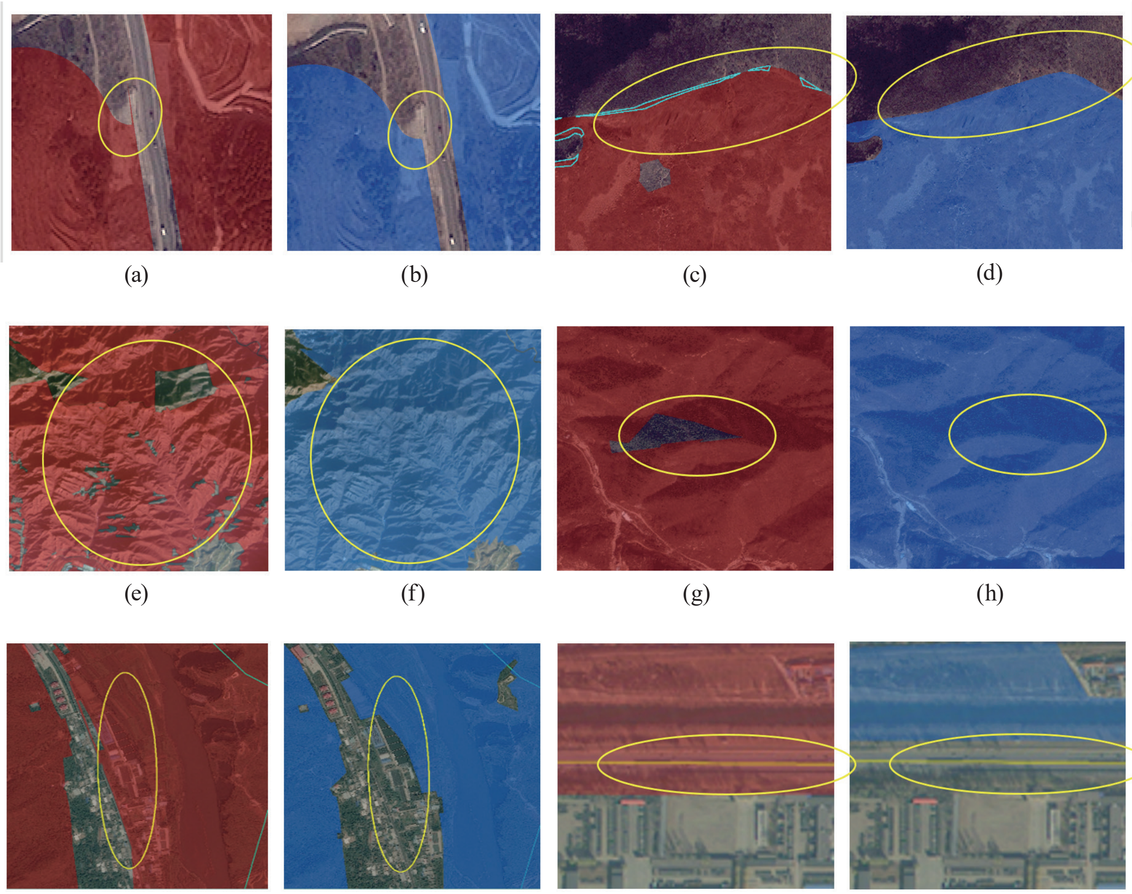
Table 3
Description of reduced plots (plaques larger than 0.01 km^2).

Serial number	Unique code	Type of check	Specific reason	Verification basis	Explanation	Area	Perimeter
						(km²)	(km)
1.	FS_ 2721	Maintain habitat integrity	Eliminate broken patches	Remove broken patches	—	0.0322	1.2013
2.	FS_ 8	Accuracy exceeded	Topological problems (serrated borders)	Remote sensing image data	—	0.0248	0.9234
3.	FS_ 1675	Accuracy exceeded	Red line cutting construction land boundary (house)	Remote sensing image data/planning	Including urban construction land	0.0124	0.8148
4.	FS_ 2121	Accuracy exceeded	Topological problems (surface breaks)	Remote sensing image data	—	0.012	1.0355
5.	FS_ 3341	Accuracy exceeded	Red line cutting boundary of construction land	Geographical conditions monitoring data, remote sensing images	—	0.0176	3.3041
6.	FS_ 5900	Contradicts plan	Special planning	Yanshan Base Core District Eastern District Control Regulations	Including urban construction land	0.0239	0.7898
7.	FS_ 5932	Contradicts plan	Lanning project	Planning project approval scope	Planning of employment base for farmers in western China	0.0201	0.9214
8.	FS_ 5987	Contradicts plan	Overlaps with urban construction land in township planning results of Fangshan District	Township-level planning achievements in Fangshan District	—	0.1044	3.7773
9.	FS_ 6008	Contradicts plan	Urban construction land/village construction land	Planning achievements of Fangshan branch of Beijing municipality	—	0.0775	3.07
10.	FS_ 5946	Contradicts status quo	Red line contains large-scale settlements	Remote sensing image data	—	0.0339	1.5983
11.	FS_ 5954	Contradicts status quo	Red line contains large-scale settlements	Remote sensing image data	—	0.0239	1.2252
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
			Total			6.6622	318.4055

Table 4
Description of supplemented plots (plaques larger than 0.01 km^2).

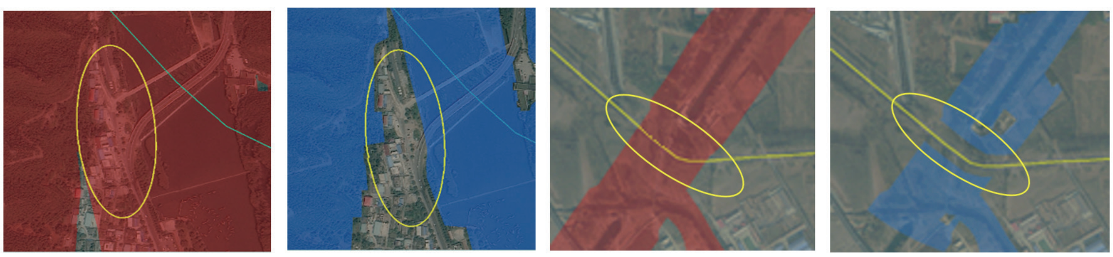
Serial number	Unique code	Type of check	Specific reason	Verification basis	Explanation	Area (km²)	Perimeter (km)
1.	FS_ 6174	Maintain habitat integrity	Bridging boundaries of various protected areas	Bridging boundaries of basic farmland	—	0.0151	0.9634
2.	FS_ 7979	Maintain habitat integrity	Connectivity adjustment	Remote sensing image data	—	0.0136	1.5339
3.	FS_ 9059	Maintain habitat integrity	Bridging natural boundaries	Remote sensing image data	—	0.018	0.7677
4.	FS_ 11042	Maintain habitat integrity	Connectivity adjustment	Convergence of nature reserves	—	0.0608	1.355
5.	FS_ 11106	Maintain habitat integrity	Bridging boundaries of nature reserves	Juma River municipal aquatic wildlife nature reserve	—	0.0206	0.6788
6.	FS_ 11111	Maintain habitat integrity	Connectivity adjustment	Remote sensing image data	—	0.1412	3.385
7.	FS_ 6120	Consistent with administrative boundaries	Add to side	Supplement based on administrative boundaries	—	0.0375	2.7184
8.	FS_ 6108	Accuracy exceeded	Unreasonable holes	Fill holes based on remote sensing image data	—	0.0224	0.8724
9.	FS_ 6110	Accuracy exceeded	Topological problems (serrated borders)	Remote sensing image data	—	0.0317	0.8376
10.	FS_ 6111	Accuracy exceeded	Unreasonable holes	Fill holes based on remote sensing image data	—	0.0121	0.6371
11.	FS_ 11058	Accuracy exceeded	Jagged border	Remote sensing image data	—	0.0196	1.3433
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Total						9.8588	425.9013

(1) Accuracy check: Make full use of the collected relevant data, check the accuracy of the red line boundary, and refine the boundary space data. The accuracy is not less than 1:10000. Figure 6 shows a comparison of the red line before and after the check.
(2) Current check: Check the large-scale settlements, high-level linear infrastructures, and other plots that contradict the status quo and are not suitable for inclusion in the red line. A comparison of charts before and after calibration is shown in Fig. 7.
(3) Consistency check with the plan: The boundary check of the ecological protection red line should be fully connected with zoning planning, special planning, and major planning and construction projects, and we coordinated the relationship between the three control lines.



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l)

Fig. 6. (Color online) Examples of accuracy check results: (a) Before the topology error was checked. (b) After the topology error was checked. (c) Before the topology error was checked. (d) After the topology error was checked. (e) Before the unreasonable hole was checked. (f) After the unreasonable hole was checked. (g) Before the topology error was checked. (h) After the topology error was checked. (i) Before the red line border overlaying the road was checked. (j) After the red line border overlaying the road was checked. (k) Before the topology error was checked. (l) After the topology error was checked.



(a) (b) (c) (d)

Fig. 7. (Color online) (a) Before the large-scale settlement included in the red line was checked. (b) After the large-scale settlement included in the red line was checked. (c) Before the high-level road included in the red line was checked. (d) After the high-level road included in the red line was checked.

The contradiction between the permanent basic farmland and the urban development boundary should be checked to ensure that the three control lines do not cross or overlap. A comparison of charts showing the results obtained before and after calibration is shown in Fig. 8.

(4) Boundary consistency check: Check and adjust the fine and independent patches caused by the plaques of adjacent areas being drawn into the boundary of the administrative area to ensure the unity and consistency of the red line boundary and the line delimiting the administrative area. A comparison of the charts before and after calibration is shown in Fig. 9.

(5) Integrity check: According to the needs of the construction of the ecological security pattern, we comprehensively consider the integrity of the regional or river basin ecosystem, and check

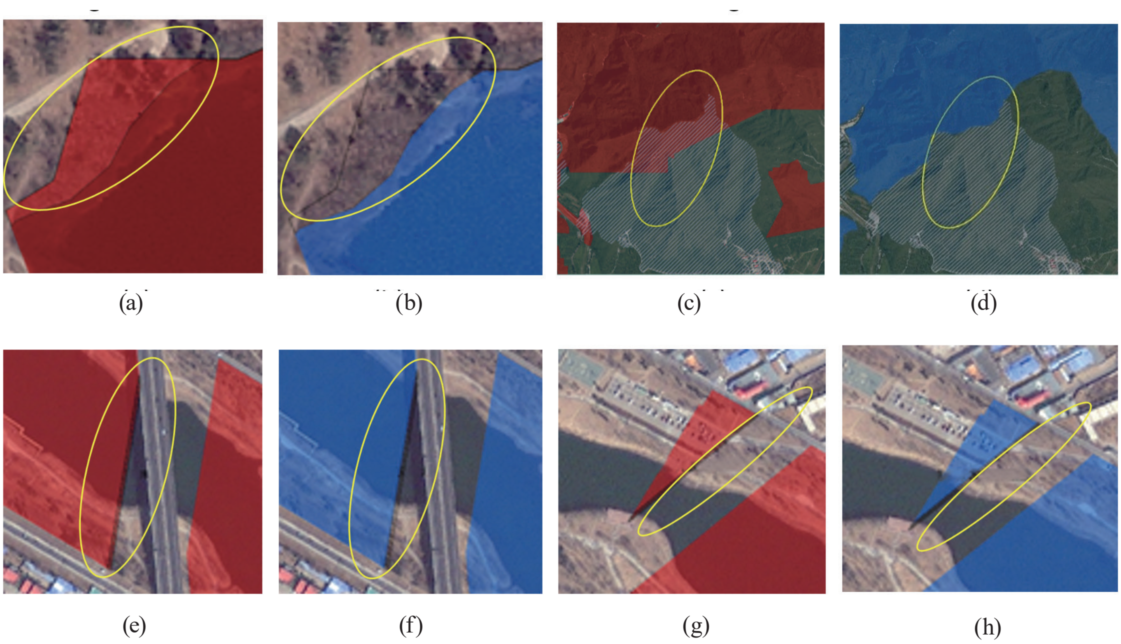


Fig. 8. (Color online) (a) Before construction land check in zoning plan in red line. (b) After construction land check in zoning plan in red line. (c), (e) Before conflict between red line and urban development boundary was checked. (d), (f) After conflict between red line and urban development boundary was checked

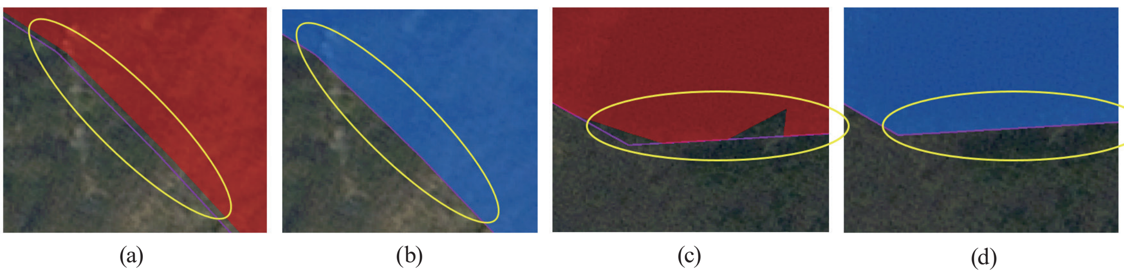


Fig. 9. (Color online) (a) Before the administrative boundary was checked. (b) After the administrative boundary was checked. (c) Before the administrative boundary was checked. (d) After the administrative boundary was checked.

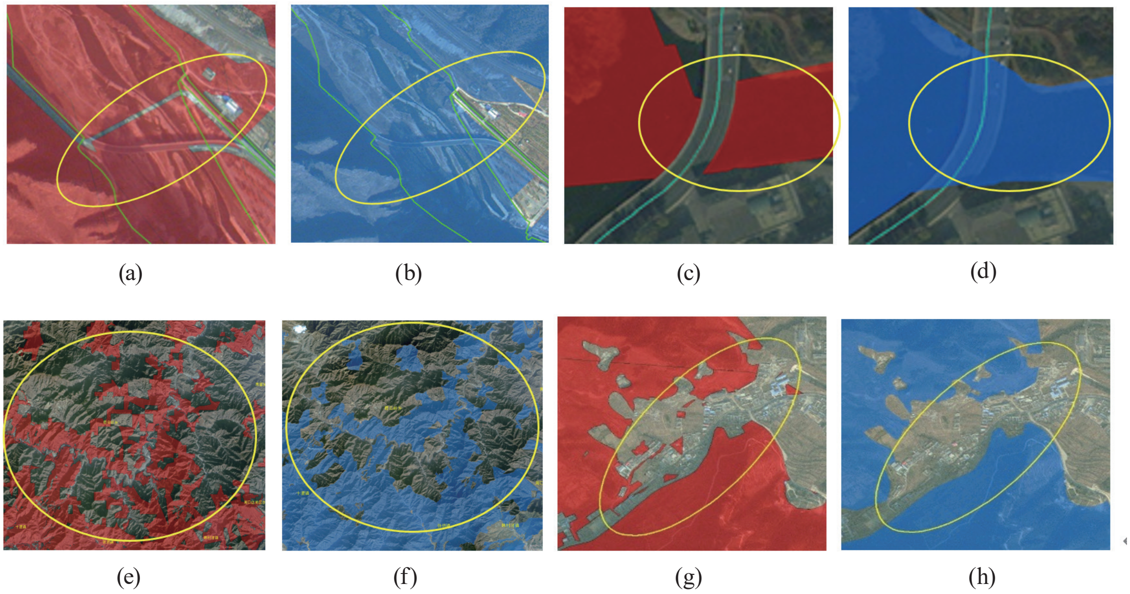


Fig. 10. (Color online) (a) Before integrity check of continuous river without interruption. (b) After integrity check of continuous river without interruption. (c) Before integrity check of river cut by viaduct. (d) After integrity check of river cut by viaduct. (e) Irregular border check to ensure complete habitat check. (f) Irregular border check to ensure complete habitat check. (g) Before removal of the broken pattern spot was checked. (h) After removal of the broken pattern spot was checked.

the red line boundary based on the natural boundaries of terrain, landforms, vegetation, and river systems as shown in Fig. 10.

5. Conclusions

The implementation of the Beijing Ecological Protection Red Line has promoted the development of "rules" and "borders" in economic and social development and helped resolve contradictions in socio-economic development planning, zoning planning, special planning, environmental protection planning, and other industrial development planning conflicts. To ensure the precise landing of the ecological protection red line in Beijing, the city has carried out border checks, which are complex and tedious tasks.

Aiming at solving the problems of the low accuracy of the red line boundary and the few boundary optimization check methods available in current ecological protection red line research, an ecological protection red line boundary check workflow, including data collection and preprocessing, based on clustering and granulation ideas was proposed, red line plaques were granulated, and a boundary check index system was constructed using the CART model and the method of checking the preparation of the plot description. This study further integrated the multi-source data in accordance with the delineation requirements of "a red line governing the ecological space" and innovatively graded and classified the contents of red line boundary checks.

The supplemented and reduced plaques were classified into five categories according to accuracy overruns, contradictions with current construction, contradictions with planning, consistency with administrative boundaries, and the maintenance of habitat integrity. A total of 11113 plaques were involved. The content of the audit was divided into five categories and 24 minor categories, including precision check, current check, coordinated check with the plan, boundary check, and integrity check, and corresponded to the "mountain, forest, field, lake, and grass" organic ecosystem. The different elements in the study were based on the "element data" and "problem solution basis" models for targeted border checks. This study will promote the construction of a world-class harmonious and livable capital in Beijing and the creation of a beautiful area around Beijing and will improve the land and space planning base map.

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References

1 W. Zhang, S. Rao, and X. Zhang: Environ. Protect. **45** (2017) 16.
2 J. Gao: Environ. Protect. **42** (2014) 17.
3 C. Zhang and Q. Liu: Beijing Plann. Constr. **3** (2015) 124.
4 C. Zou, L. Wang, and J. Liu: Biodiversity **23** (2015) 716.
5 B. Yang, J. Gao, and C. Zou: China Dev. **14** (2014) 1.
6 X. Wu, S. Liu, F. Cheng, X. Hou, Y. Zhang, S. Dong, and G. Liu: Case Stud. Southwest China **1224** (2018) 616.
7 W. Shang, D. Yu, and Y. Zhai: J. Nat. Sci. Harbin Normal Univ. **15** (2003) 168.
8 W. Jin and W. Lin: Ecol. Red Lines **25** (2016) 3587.
9 P. He, J. Gao, W. Zhang, S. Rao, C. Zou, J. Du, and W. Liu: Land Use Policy **71** (2018) 245.
10 X. Xu, G. Yang, and Y. Tan: Ecol. Indic. **96** (2019) 635.
11 X. Xu, Y. Tan, G. Yang, and J. Bo: Land Use Policy **79** (2018) 447.
12 C. Wang, G. Sun, and L. Dang: Sustainability **7** (2015) 9461.
13 X. Zhang, Z. Wang, and J. Lin: Sustainability **7** (2015) 9924.
14 Y. Zhang, Y. Liu, Y. Zhang, X. Kong, and Y. Jing: Sustainability **11** (2019) 2025.
15 W. Hu, W. Yu, Z. Ma, G. Ye, E. Dang, H. Huang, D. Zhang, and B. Chen: Sustainability **11** (2019) 6372.
16 J. Gao, C. Zou, and H. Zheng: Environ. Prot. **6** (2011) 26.
17 B. Wang, T. Wang, and Q. Wang: J. Desert Res. **39** (2001) 10.
18 C. Zou, M. Xu, and N. Lin: Environ. Prot. **43** (2014) 55.
19 Q. Han: Harbin Institute of Technology (2015).
20 W. Hong, R. Jiang, C. Yang, F. Zhang, M. Su, and Q. Liao: Ecol. Indic. **69** (2016) 540.
21 J. Lin and X. Li: Sustainable Cities Soc. **46** (2018).
22 L. Bai, C. Xiu, X.Feng, and D. Liu: Habitat Int. **9** (2019) 102042.
23 X. Liu, L. Liu, and Y. Peng: Ecol. Modelling (2018) S0304380016304240.
24 Y. Yang, G. Song, and S. Lu: Ecol. Indic. (2020) 105754.
25 B. Li, F. Huang, L. Qin, H. Qi, and N. Sun: Remote Sens. **11** (2019) 2513.

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