

Article

Methodology for Wildland–Urban Interface Mapping in Anning City Using High-Resolution Remote Sensing

Feng Jiang ^{1,2}, Xinyu Hu ^{1,2}, Xianlin Qin ^{1,2,*} , Shuisheng Huang ^{1,2} and Fangxin Meng ^{1,2}

¹ Research Institute of Forest Resource Information Techniques, Chinese Academy of Forestry, Beijing 100091, China; camellia_0601@163.com (F.J.); hxyuinu@163.com (X.H.); huangss@caf.ac.cn (S.H.); mengfx0208@163.com (F.M.)

² Key Laboratory of Forestry Remote Sensing and Information System, National Forestry and Grassland Administration, Beijing 100091, China

* Correspondence: qxl@ifrit.ac.cn; Tel.: +86-10-62888847

Abstract: The wildland–urban interface (WUI) has been a global phenomenon, yet parameter threshold determination remains a persistent challenge in this field. In China, a significant research gap exists in the development of WUI mapping methodology. This study proposes a novel mapping approach that delineates the WUI by integrating both vegetation and building environment perspectives. GaoFen 1 Panchromatic Multi-spectral Sensor (GF1-PMS) imagery was leveraged as the data source. Building location was extracted using object-oriented and hierarchical classification techniques, and the pixel dichotomy method was employed to estimate fractional vegetation coverage (FVC). Building location and FVC were used as input for the WUI mapping. In this methodology, the threshold of FVC was determined by incorporating the remote sensing characteristics of the WUI types, whereas the buffer range of vegetation was refined through sensitivity analysis. The proposed method demonstrated high applicability in Anning City, achieving an overall accuracy of 88.56%. The total WUI area amounted to 49,578.05 ha, accounting for 38.08% of Anning City’s entire area. Spatially, the intermix WUI was predominantly distributed in the Taiping sub-district of Anning City, while the interface WUI was mainly concentrated in the Bajie sub-district of Anning City. MODIS fire spots from 2003 to 2022 were primarily clustered in the Qinglong sub-district, Wenquan sub-district, and Caopu sub-district of Anning City. Our findings indicated a spatial overlap between the WUI and fire-prone areas in Anning City. This study presents an effective methodology for threshold determination and WUI mapping, making up for the scarcity of mapping methodologies in China. Moreover, our approach offers valuable insights for a wise decision in fire risk.

Keywords: GF1-PMS; mapping methodology; sensitivity analysis; WUI; wildfire risk



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1. Introduction

Forest fires are among the major natural disasters confronting humanity and remain a significant global concern [1–3]. Forest fires have affected a total global area of 1.033 billion ha, with an annual average of 46.95 million ha from 2001 to 2022 [4]. A series of catastrophic fires in eastern Australia devastated approximately 5.8 million ha [5]. The 2023 Hawaii wildfires resulted in 97 fatalities and over USD 5 billion in losses [6]. As global warming intensifies and extreme weather events become more frequent, the impacts of forest fires are escalating on society, the economy, and ecosystems, particularly WUI fires. WUI fires are characterized by a high risk of occurrence, complex fire environments, unpredictable fire behavior, severe consequences, and significant challenges in emergency response [7].

In 2017, a WUI fire in central Portugal claimed 65 lives, injured more than 200 people, and destroyed over 1000 buildings [8]. Wildfires broke out in Los Angeles in many places on 7 January 2025. The Eaton Fire and the Palisades Fire caused at least 28 deaths and 13 injuries. The fires damaged over 12,300 structures and approximately 40,000 ha [9]. With the continued advancement of the global economy and increasing urbanization, the WUI has been expanding in recent years [10]. The monitoring and management of WUI fires have become a focal point of wildfire prevention and control worldwide.

China also faces wildfire challenges in the WUI. Several concepts analogous to the WUI have been proposed in earlier research, such as “urban mountain areas” [11], “urban-rural fringe zones” [12], and “urban-rural transition zones” [13]. The restructuring of Chinese government agencies in 2018 unified the management of forest and urban fire prevention. The WUI and its associated fire management have garnered increasing attention from various stakeholders. As the WUI management has only gained attention relatively recently, wildfire risk has long been a focal issue. Scholars have conducted extensive studies on fire risk and fire management [14–17]. However, WUI mapping methodology in China remained under-researched.

Anning City is located in the core region of Yunnan Province, China. Its topography is characterized by intermontane basins and mountainous to semi-mountainous terrain. Anning City has a vegetation coverage of 52.6%, an urbanization rate of 84.92%, and exhibits a complex mosaic of vegetated areas and built structures, making it a typical WUI. According to Jiang et al. [18] and Forestry Administration [19], Anning City has been classified as a key forest fire prevention area within the Yunnan–Guizhou Plateau and the first-level fire risk area. In recent years, Anning’s WUI fires have occurred frequently. Notable incidents include the “3.29” wildfire that burned 1333.33 ha and directly threatened six towns and villages; the “5.9” wildfire affected 170.1 ha; and the “4.13” wildfire resulted in a burned area of 67 ha.

Current WUI delineation are primarily driven by international approaches. These mapping methods can be broadly categorized into four groups based on the variations in calculating building data: demographic unit-based mapping method [20,21], individual building-based mapping methods [22,23], point-based mapping methods [24–26], and central pixel-based mapping methods [27].

A comprehensive analysis of these approaches revealed that there exists a significant challenge to the transferability of parameters threshold and methodologies. Many international studies adopted mainstream thresholds without validating their suitability for specific environments. The mainstream thresholds have exerted significant influence and have been widely adopted in subsequent studies [28,29]. The thresholds were calculated based on census blocks, building density is 6.17 housing units/km², and wildland vegetation is 50% [30]. The absence of census block data in China poses challenges for the direct application of such thresholds.

Moreover, the choice of mapping method appeared to be influenced more by the country’s location where the study was conducted rather than by analysis region scales. In France, the mapping method was generally based on the method proposed by Lampin-Maillet et al. [22], while in the United States, the approach developed by Radeloff et al. [30] was commonly used. The applicability of these methods in China is unknown. Thus, the existing mapping methods cannot be directly applied to the WUI delineation in China, as they failed to adequately account for local environment, socio-economic, and geographical factors.

The WUI is widely distributed in China, but there is a lack of a method for determining parameter thresholds and a comprehensive mapping methodology. The aim of our study is to propose a method for threshold determination and to develop a zoning framework,

thereby offering insights into the challenge of the threshold in WUI mapping and providing a technical reference for county-level WUI zoning in China.

2. Materials and Methods

2.1. Study Area

Anning City is located in the southwestern part of Kunming, Yunnan Province (Figure 1), lying between $102^{\circ}08'–102^{\circ}37'$ E and $24^{\circ}31'–25^{\circ}06'$ N. The region features a mid-subtropical climate typical of low-latitude, high-elevation zones, characterized by mild seasonal temperature variation and a distinct dry-wet seasonality. The topography is generally higher in the southeast and lower in the northwest, with elevations ranging from 1680 to 2617.7 m and an average altitude of approximately 1800 m. The terrain is primarily composed of intermontane basins and hilly to mountainous areas, with relatively moderate topographic variation across the region.

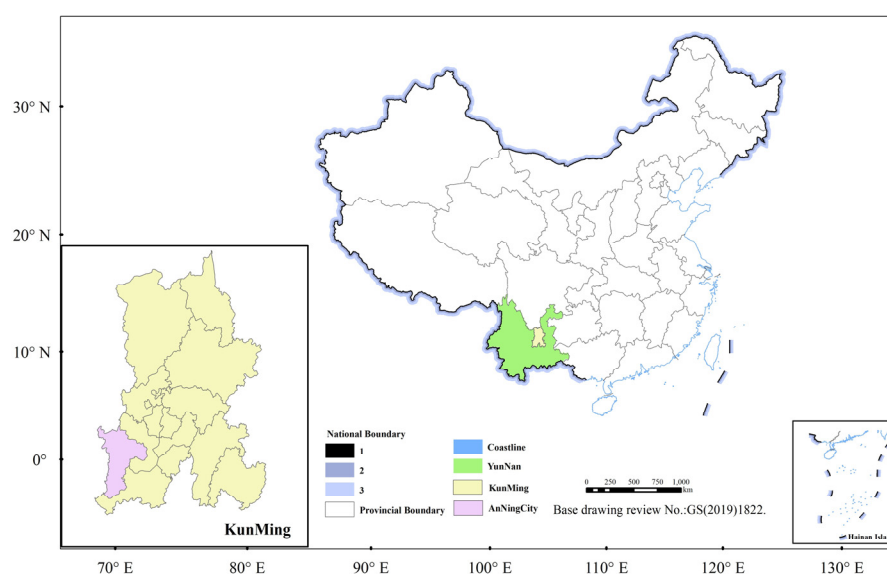


Figure 1. Overview of the study area.

The annual mean temperature is 15.3°C . The urbanization rate has reached 84.92%, and the region boasts a forest greening rate of 68.82%. Total forest stock volume stands at 4.819 million m^3 , with a forest coverage rate of 52.6%. Notably, forest coverage reaches 68.28% in the Qinglong sub-district, 70% in the Caopu sub-district, and exceeds 80% in the Wenquan sub-district.

2.2. Data Source and Preprocessing

GF1-PMS satellite images were downloaded from the China Resource Satellite Application Center (<https://data.cresda.cn/> (accessed on 28 February 2024)), comprising three scenes on 5 January 2024, and two scenes on 9 January 2024. To produce a 2 m GF1 fusion image of Anning City, these images were preprocessed with a series of steps using ENVI 5.3 software, including radiometric calibration, atmospheric correction (FLAASH), geometric correction (RPC), image fusion (Gram–Schmidt pan sharpening), and regional clipping (Figure 2). Subsequently, building data and fractional vegetation coverage (FVC) were extracted from these images.

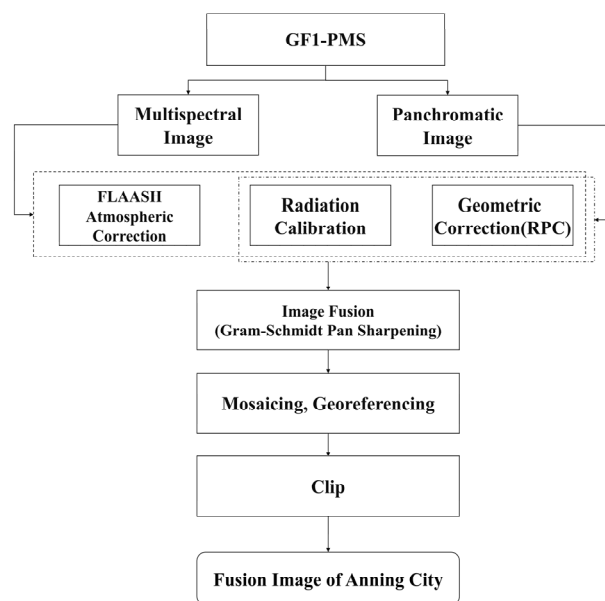


Figure 2. Flowchart of Anning's GF1-PMS preprocessing.

The boundary vector data were sourced from the 1:1,000,000 Public Version of Basic Geographic Information Data (2021), published by the National Basic Geographic Information Center. Urban boundary vector data were obtained from the download link provided by Li [31]. Fire spot vector data were acquired from NASA's Terra/Aqua MODIS satellite data (MOD14/MYD14 V6.1) in shapefile format from 2003 to 2022. Land cover data were derived from NASA's MOD12Q V6.1 product. For a further analysis of the relationship with the WUI, fire spots were selected, which had a confidence level above 75% and were located in the forest-shrub-grass regions.

2.3. Methods

2.3.1. Vegetation Coverage Threshold Determination Method

Based on randomly generated sample points and assisted by visual interpretation of the intermix characteristic, intermix sample points were generated. The visual interpretation was guided by the WUI definition and 0.5 m online satellite imagery in ArcGIS Pro 3.1.6. A total of 1000 intermix sample points were selected; 1000 sample points were considered as the typical size for classification [32]. Those samples were good representatives that combined the spatial features of the vegetation and buildings in Anning City. The selected sample points were divided into a test set and a validation set in a ratio of 7:3. Then, 700 sample points were used to determine the threshold, while the other 300 points were reserved for validating the mapping accuracy. The vegetation coverage threshold was defined as the mean vegetation coverage value of the 700 sample points.

2.3.2. Sensitivity Analysis

Sensitivity analysis, a technique for evaluating threshold stability, was employed to determine the optimal distance threshold for building influence. The core idea was to examine the relationship between variations in the influencing factors and the corresponding changes in the results. For instance, Li [20] evaluated distances of 1.2 km, 2.4 km, and 4.8 km to assess the impact of firebrands on the buildings. They concluded that when doubling or halving the distance resulted in a less-than-proportional change in the WUI area, the threshold was stable.

We employed ten buffer distances for the buildings, including 250 m, 500 m, 750 m, 1000 m, 1250 m, 1500 m, 1750 m, 2000 m, 2200 m, and 2400 m. For each buffer, the areas and

proportions of both the WUI and vegetation areas were calculated. We used the change rate of the indicators to determine the stable buffer distance threshold. First, the change rates of the circular area formed by different buffer distances were calculated. Second, the rates of change in the corresponding indicator values with buffer distance were computed. The ratios between the indicator's change rates and the circular area's change rates were used to express the sensitivity of the indicators to buffer distance. Finally, we integrated the ratios across different buffer distances. The distance with the smallest overall variation ratios was identified, and considered the optimal buffer distance around the buildings.

2.3.3. WUI Mapping

Buildings and the FVC are the two most important elements in the WUI, so our mapping method considered the buildings and the vegetation coverage, respectively. The WUI results encompassed the buildings ignited by the firebrands and the vegetation areas surrounding the buildings. Firstly, parts of the buildings were identified as intermix buildings, which were identified by logical operations of the building and high vegetation coverage regions. Similarly, the interface buildings were defined by applying the same operation between non-intermix building areas and the buffer zone of the high FVC regions. The buildings in the WUI are demarcated through the above steps. For the vegetation areas surrounding the buildings, we adopted buffer analyses to define. Finally, we selected five accuracy evaluation indicators to verify the delineated WUI. Notably, during the mapping process, urban green spaces were excluded by using the central urban boundary data. The workflow of the mapping process is illustrated in Figure 3.

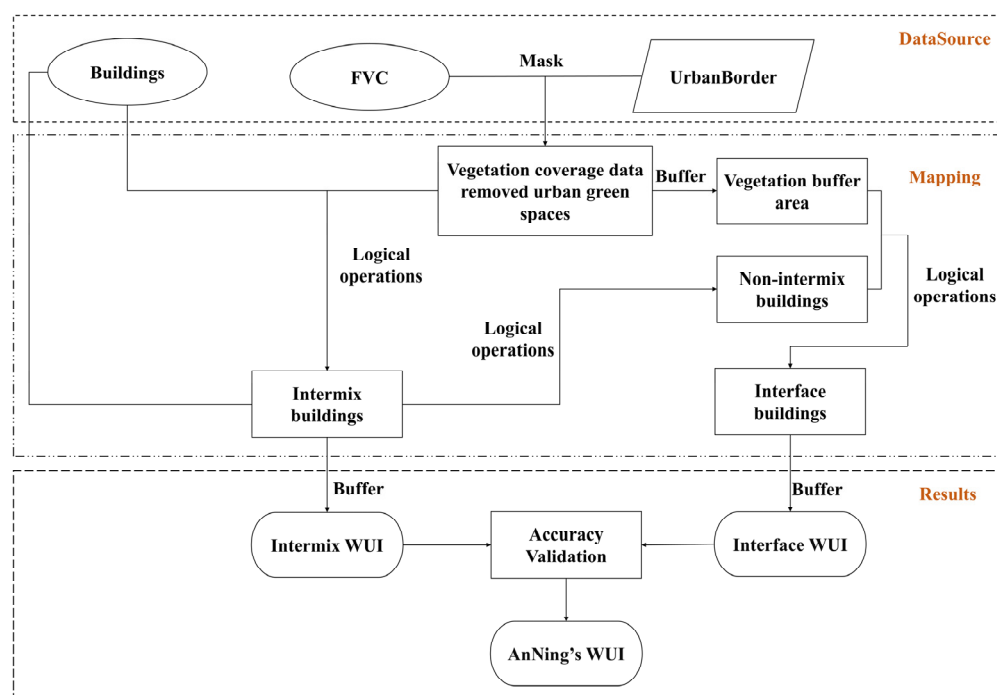


Figure 3. Flowchart of Anning's WUI mapping method.

2.3.4. Accuracy Verification

For each category (intermix WUI, interface WUI, and non-WUI), 300 validation sample points were selected following the same methodology used for FVC sample points. Five indicators were calculated, including accuracy, precision, recall, F1-score, and kappa coefficient. The formulas for each metric are as follows:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (1)$$

$$Precision = \frac{TP}{TP + FP} \quad (2)$$

$$Recall = \frac{TP}{TP + FN} \quad (3)$$

$$F1 - Score = \frac{2 * Precision * Recall}{Precision + Recall} \quad (4)$$

$$Kappa = \frac{p_0 - p_e}{1 - p_e} \quad (5)$$

Equations (1)–(3), where TP represents the number of correctly classified as intermix sample points; TN denotes the number of correctly classified as non-intermix sample points; FN refers to the number of misclassified as non-intermix WUI sample points; and FP indicates the number of misclassified as intermix sample points. The interface and non-WUI are the same. P_0 represents the sum of correctly classified samples in each category divided by the total number of samples. P_e represents the sum of the true numbers multiplied by the predicted numbers divided by the square of the total number of samples.

3. Results

3.1. Parameter Thresholds for WUI Mapping

3.1.1. Threshold of FVC

The “Extract Values to Points” function in ArcGIS 10.6 was applied to extract the value of FVC of each point among the 700 intermix sample points. Statistical algorithms were used on these sample points. We calculated the standard deviation to measure the degree of data dispersion, as it reflects the extent to which individual data points deviate from the mean within a dataset. The standard deviation of this dataset is 0.26. The smaller the standard deviation, the more concentrated the values are around the mean. As shown in Figure 4, the average value of these sample points was 45%.

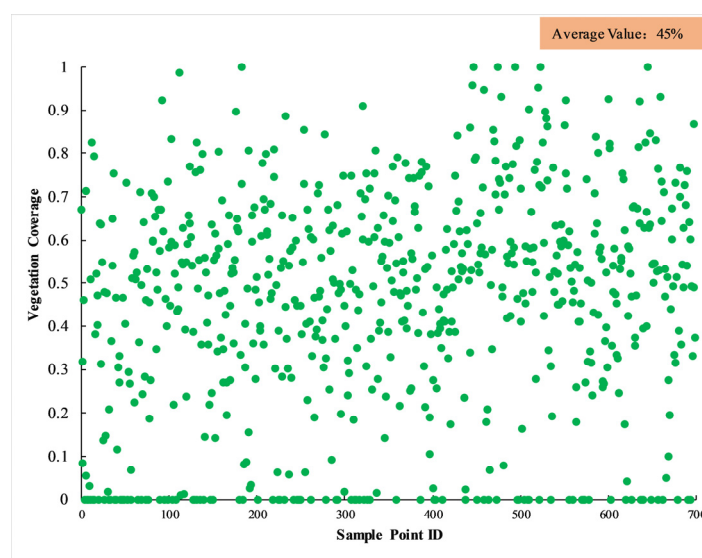


Figure 4. Scatter plot of FVC of 700 intermix sample points.

3.1.2. Threshold of Vegetation Range Surrounding Building

Sensitivity analysis was employed to investigate the extent of vegetation surrounding buildings across different types of WUI. As the buffer distance varied, several metrics were calculated: the area of the intermix (MA), the intermix proportion relative to the total area of Anning City (MAP), the area of vegetation within the intermix (MVA), and the

proportion of vegetation within the intermix (MVAP). The change of four indicators with buffer distance is shown in Figure 5.

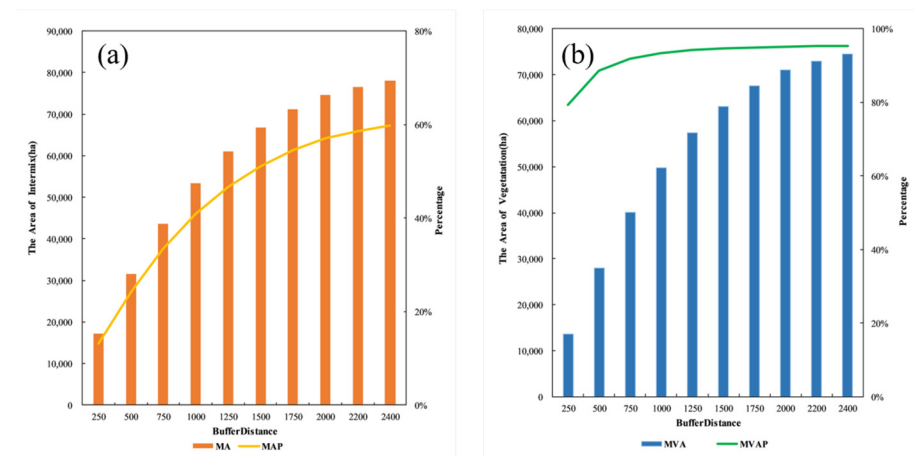


Figure 5. Results of the intermix at different buffer distances. (a) The intermix area and proportion; (b) vegetation area and proportion in the intermix area.

The rate of change relationship between buffer distance and these four metrics was examined, including the rate of change in intermix area (MARo), rate of change in the proportion of intermix area to the total area (MAPRo), rate of change in vegetation area within the intermix (MVARo), and rate of change in the proportion of vegetation area within the intermix (MVAPRo), as shown in Figure 6.

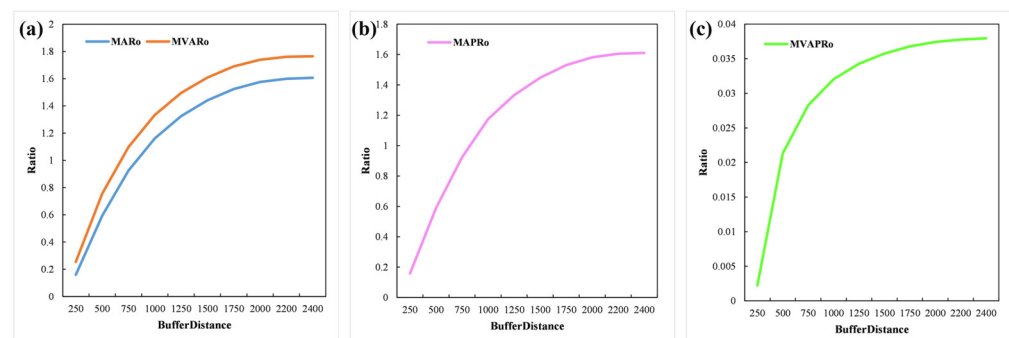


Figure 6. Changes in the four indicators of intermix areas in different buffer distances. (a) Changes in the ratio of intermix area and vegetation area; (b) changes in the ratio of intermix area proportion; (c) changes in the ratio of vegetation area proportion.

From Figure 5, MA, MAP, MVA, and MVAP exhibit an increasing trend with the expansion of buffer distance, while the increase gradually declines. According to Figure 6, MARo, MAPRo, MVARo, and MVAPRo show an increasing trend, indicating that larger buffer distances result in greater fluctuations and reduced stability. When the buffer distance reaches 250 m, these four indicators exhibit the smallest relative rate of change. The rate of change at 250 m is significantly lower than that at other buffer distances, suggesting the highest stability. The threshold for the vegetation range of the intermix WUI is determined to be 250 m.

The vegetation range of the intermix WUI was determined to be 250 m. The buffer distances combination was applied to investigate the vegetation range of the interface WUI. The 250 m buffer was combined with ten buffer distances. The area of the interface (FA), the interface proportion relative to the total area of Anning City (FAP), the area of vegetation within the interface (FVA), and the proportion of vegetation within the interface (FVAP)

were calculated (Figure 7). From Figure 7, FA, FAP, FVA, and FVAP appear an overall increasing trend, while the increase gradually decreases. As observed from the trend of FVAP, the indicator stabilizes at a buffer distance of 750 m.

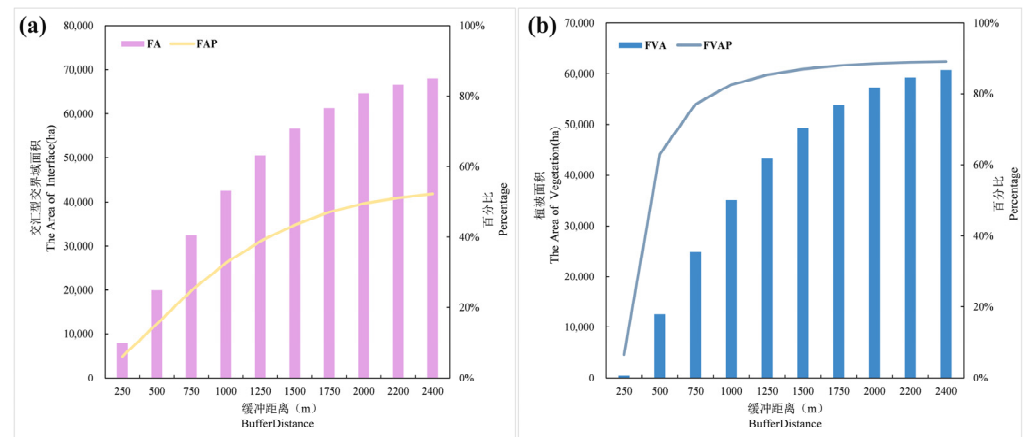


Figure 7. Results of the interface at different buffer distances. (a) The interface area and proportion; (b) vegetation area and proportion in the interface area.

The rate of change relationship between buffer distance and these four metrics was examined, including the rate of change in interface area (FARo), rate of change in the proportion of interface area to the total area (FAPRo), rate of change in vegetation area within the interface (FVARo), and rate of change in the proportion of vegetation area within the interface (FVAPRo), as shown in Figure 8.

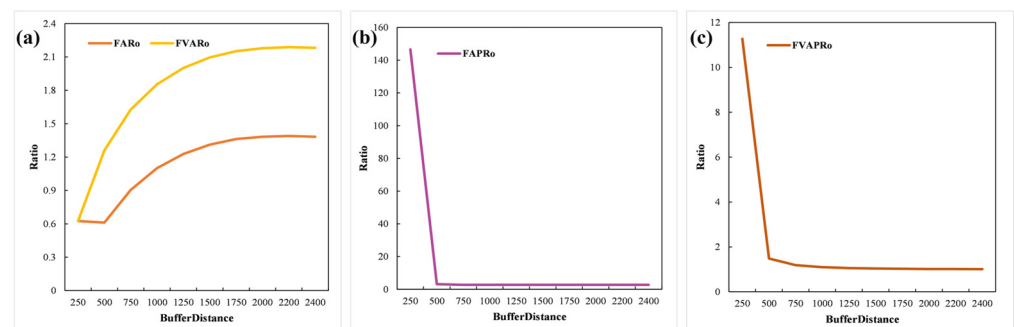


Figure 8. Changes in the four indicators of interface areas in different buffer distances. (a) Changes in the ratio of interface area and vegetation area; (b) changes in the ratio of interface area proportion; (c) changes in the ratio of vegetation area proportion.

Regarding the variation in FARo, FAPRo, FVARo, and FVAPRo (Figure 8), FARo generally shows an increasing trend, while FVARo reaches its lowest value at 500 m, with only a minor difference compared to 750 m. FAPRo and FVAPRo display an overall decreasing trend and stabilize at 750 m. Considering the combined evaluation of all four indicators, 750 m is selected as the threshold for the vegetation range of the interface WUI.

3.2. Results of WUI Mapping

According to the thresholds and mapping process outlined in the aforementioned analysis, the intermix refers to the areas of buildings within FVC greater than 45% and the surrounding vegetation within a 250 m buffer from the buildings. The interface includes buildings within a 2400 m buffer from vegetation where FVC is higher than 45% and the surrounding vegetation within a 750 m buffer from the buildings. The distribution of WUI is presented in Figure 9. From Figure 9, the WUI is predominantly clustered in the northern

part of Anning City, with significantly fewer areas observed in the southern region. The intermix is primarily located in the northwest, northeast, and along the central axis of the city. The interface is distributed around the intermix, interspersing with it.

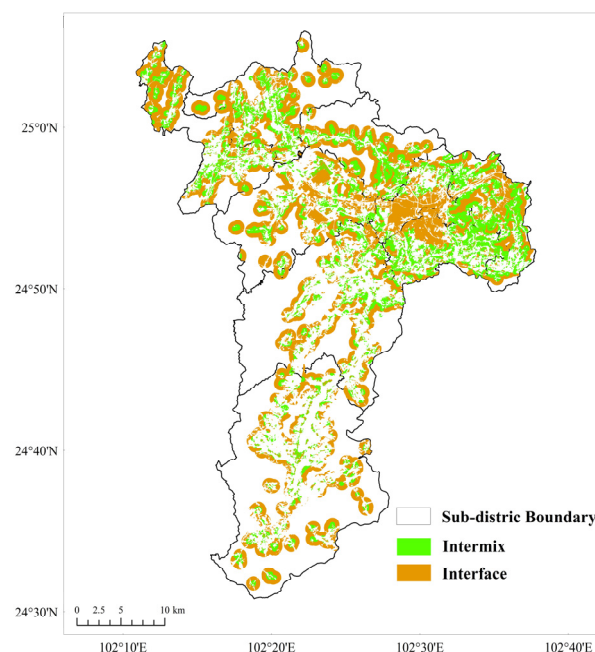


Figure 9. The distribution of WUI in Anning City.

3.3. Accuracy Validation Results

An equal number of interface and non-WUI validation sample points were selected by using the same method as the intermix. The intermix and interface sample points were primarily located in areas where buildings and vegetation intersect, while the non-WUI sample points were mainly distributed within vegetation zones or urban green spaces. Overall, those sample points are relatively evenly distributed across the study area. Table 1 shows the accuracy evaluation results. The values of all four indicators for intermix, interface, and non-WUI exceeded 80%. Specifically, the overall accuracy was 88.56% and the kappa coefficient was 0.83, with the F1-score for the interface being 0.87, the F1-score for the intermix being 0.88, and the F1-score for the non-WUI being 0.91. Overall, the approach is reliable and operational.

Table 1. The results of accuracy evaluation for the WUI.

Sample Category	Interface Samples	Intermix Samples	Non-WUI Samples
Interface Samples	245	31	24
Intermix Samples	15	261	24
Non-WUI Samples	5	4	291
Precision	81.67%	87.00%	97.00%
Recall	92.45%	88.18%	85.84%
F1-Score	0.87	0.88	0.91
Accuracy		88.56%	
Kappa		0.83	

3.4. Distribution Characteristics of the WUI

3.4.1. Quantity Characteristics

(1) Area of the intermix buildings and interface buildings in the WUI

From the statistical results of building area (Table 2), the area of the building within WUI is 10,959.93 ha, the building within the intermix reaches a total of 3584.28 ha, and the building within the interface is 7375.65 ha. The total area of buildings accounts for 10% of the total area of Anning City. From the buildings in different WUI areas, the buildings within the intermix account for 20.74% of the total area of the intermix area, and the buildings within the interface account for 22.84% of the total area of the interface area. In general, the small occupation of the building areas indicates that the primary contributor to the WUI area is the outward range of vegetation.

Table 2. Statistical results on the area and proportion of the building.

Building Types	Area (ha)	The Proportion to the Total Area of the Anning City (%)	The Proportion to Total Building Area in Anning City (%)	The Proportion to the WUI Area (%)
Intermix	3584.28	2.75	32.68	20.74
Interface	7375.65	5.67	67.24	22.84

(2) Vegetation area in the WUI

The total area of vegetation is 38,618.12 ha, accounting for 29.66% of the Anning City area and 47.64% of the total vegetation area in Anning City (Table 3). The vegetation within the intermix is 13,699.65 ha, accounting for 79.26% of the intermix area, and the vegetation within the interface is 24,918.47 ha, accounting for 77.16% of the interface area.

Table 3. Statistical results on the vegetation area and proportion.

Vegetation Type	Area (ha)	The Proportion to the Total Area of the Anning City (%)	The Proportion to Total Vegetation Area in Anning City (%)	The Proportion to the WUI Area (%)
Intermix	13,699.65	10.52	16.90	79.26
Interface	24,918.47	19.14	30.74	77.16

The vegetation area of the intermix is less than the interface. However, the proportion of vegetation area within the intermix is higher than within the interface. This discrepancy arises from the different outward expansion distances of the intermix and interface buildings.

(3) Total area of the WUI

Statistical analysis shows that Non-Wui areas dominate Anning City, accounting for 61.92% of the total area of the city, and WUI areas are 49,578.05 ha, accounting for 38.08% of the city's total area (Figure 10). The interface covers a larger area than the intermix, with 17,283.93 ha in the intermix area (13.28%), and 32,294.12 ha in the interface area (24.80%).

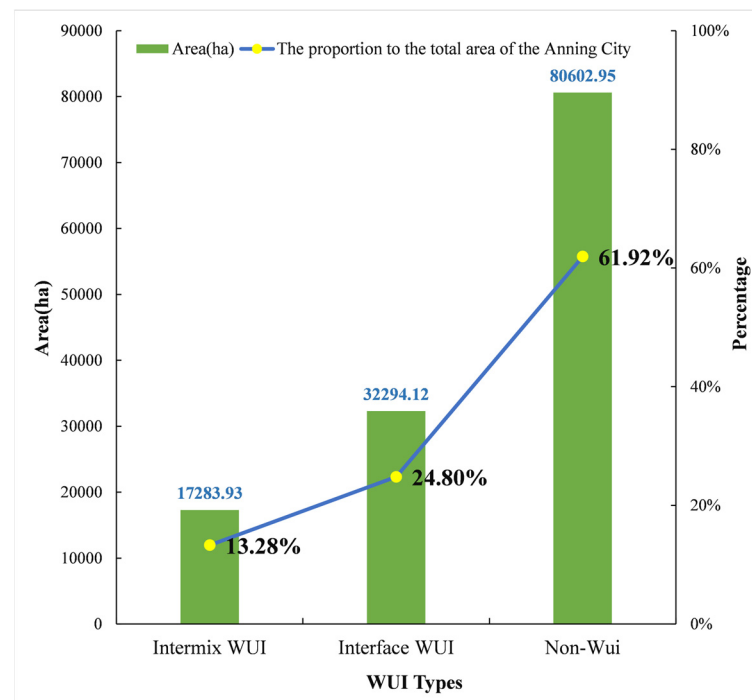


Figure 10. Statistical results on the area and proportion of the WUI and Non-Wui.

3.4.2. Spatial Distribution Characteristics

To gain a more detailed understanding of the specific distribution of the WUI, the nine sub-districts within the city were used as statistical units, and the distribution of both intermix and interface WUI was analyzed separately, as shown in Figure 11.

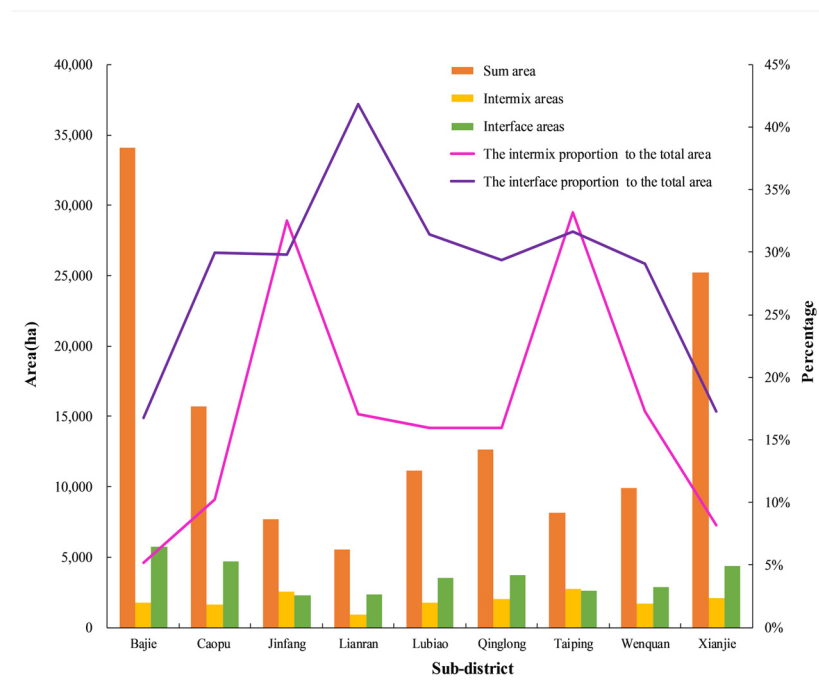


Figure 11. Statistical result of the area and proportion of intermix WUI and interface WUI in each sub-district.

The results indicate that among the nine sub-districts, Bajie has the largest WUI area, while Lianran has the smallest. The total WUI area in Bajie is more than twice that of Lianran. In terms of the distribution of two WUI types, Taiping leads in the intermix WUI

area, followed by Jinfang, whereas Bajie has the highest shares of interface WUI area, with Xianjie in second place. Lianran has the least intermix WUI area, with Caopu next, while Jinfang occupies the smallest interface WUI area, followed by Lianran.

About the proportion of the two WUI types, the intermix WUI area in Bajie accounts for the highest percentage (33.47%), while seven sub-districts have an intermix WUI area proportion of less than 30%, with the lowest being 5.20%. The highest proportion of the interface WUI area is 42.36%, with the lowest being 16.81%. Four sub-districts have a proportion of less than 30%. Due to differences in the area of each sub-district, some exhibit a larger total WUI area but a lower proportion, while others show the opposite result. For instance, Bajie has a greater intermix WUI area than Lianran, whereas it holds the lowest proportion among the nine sub-districts.

3.4.3. Distribution Relationship Between the WUI and MODIS Fire Spots

(1) Spatial distribution characteristics of forest, shrub, and grass fire spots

These fire spots are predominantly distributed in the northwestern, northeastern, and central-western areas near the city's boundaries, as well as in the southern regions, including Qinglong, Wenquan, Caopu, and Bajie (Figure 12).

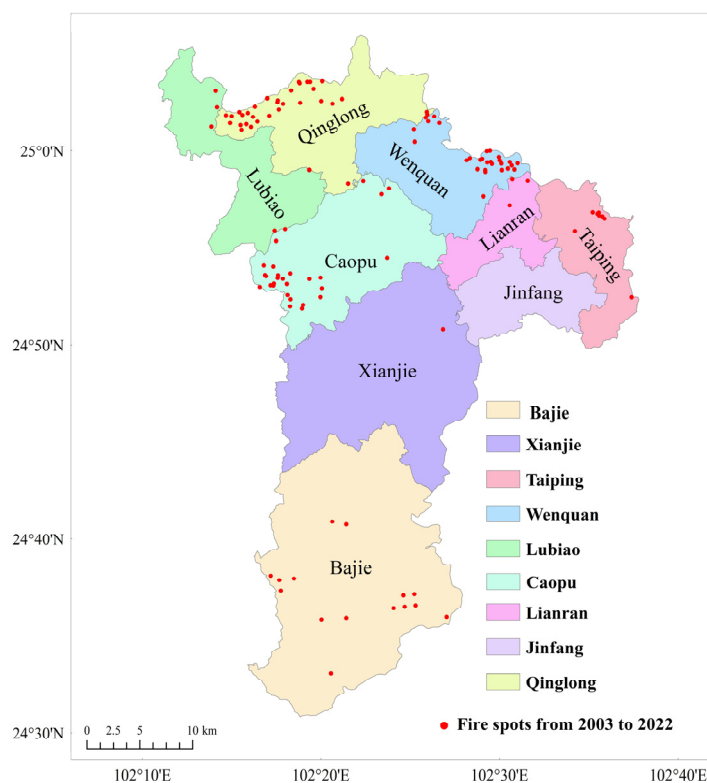


Figure 12. Distribution of forest, shrub, and grassland fire spots in Anning City from 2003 to 2022.

Figure 13 illustrates that MODIS fire spots are observed only in forests and grasslands. Notably, the number of fire spots in grasslands exceeds that in forests, with grasslands accounting for 59.84% of the total fire spots.

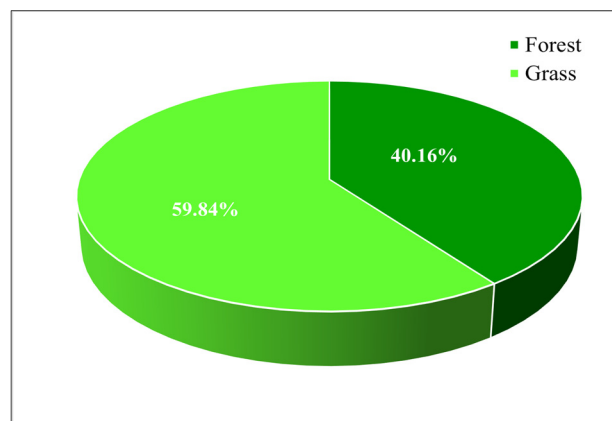


Figure 13. The proportion of fire spots in forest and grassland from 2003 to 2022.

(2) The association of the WUI with fire spots

The locations of fire spots are integrated with the distribution of the WUI (Figure 14). Subsequently, we carry out a statistical analysis on the proportion of fire spots within the WUI. The results reveal that 33.86% of the fire spots are located in the WUI, with 27.56% distributed in the interface WUI area and 6.30% in the intermix WUI area.

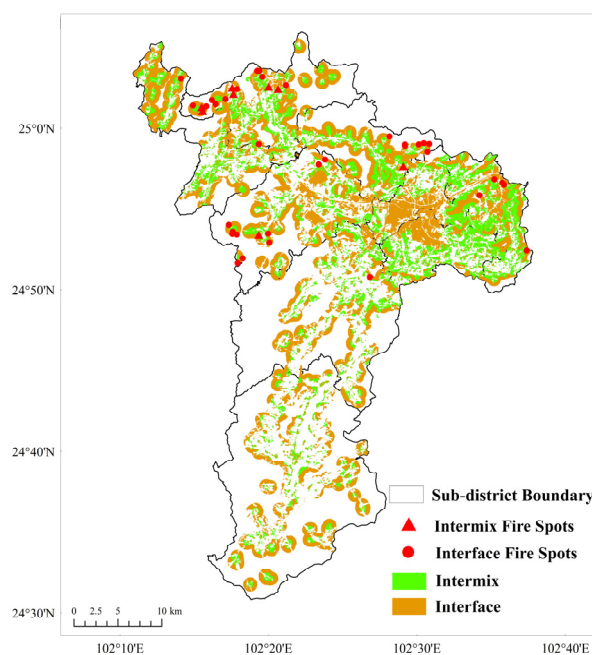


Figure 14. Distribution of forest, shrub, and grass fire spots in the WUI. Fire spots are identified by different WUI. Triangle refers to fire spots, which were located in intermix areas. Dots represent fire spots that were distributed in interface area.

Lastly, an analysis of the location of fire spots and the WUI in Anning City reveals a degree of overlapping in spatial distribution. Fire points are primarily concentrated in Qinglong, Wenquan, Caopu, Taiping, and Bajie. The WUI area of Bajie, Caopu, Qinglong, and Taiping has exceeded 5000 ha. The spatial patterns of fire spots and the WUI can be explained by factors such as vegetation coverage, regional policies, and climatic conditions.

In sub-districts with large WUI areas, high vegetation coverage, abundant combustible materials, and favorable climate conditions mean that even minimal human-induced ignition can trigger wildfires. Anning City has a distinct dry and wet season, sufficient

sunshine, and good vegetation conditions. Specifically, Bajie has a vegetation coverage of 61%, Qinglong is 68.28%, Caopu is 70%, and Wenquan is over 80%.

Moreover, the interaction between human activities and the natural environment has intensified. In recent years, Anning City has been undergoing high-quality economic development. Each township has leveraged its unique characteristics to actively promote cultural tourism, and steadily advances urban construction and rural revitalization. For example, Taiping is committed to developing in the “Kunming–Taiping–Anning” integrated development axis, leading the city’s expansion southward and fostering regional integration.

These observations suggest that both vegetation coverage and human activity play significant roles in the occurrence of the WUI wildfires. Preventive measures should include timely removal of combustible materials, raising fire awareness among forest visitors, and strengthening fire safety education for residents by relevant authorities.

4. Discussion

Currently, Anning City possesses a set of WUI maps derived from Schug’s global WUI dataset. To test the usability of our approach, our method (hereinafter referred to as RS_ANWUI) is compared with Schug’s, focusing on the calculation of parameters, the establishment of parameter thresholds, the differences in the maps, and relevance to fire indicators (fire spots and fire perimeters). Furthermore, we discussed the limitations and broader applicability of the RS_ANWUI method.

(1) Parameter Differences of Calculation Method

In Schug’s approach, building and wildland vegetation cover were derived through a window-based statistical method, making both building density and wildland vegetation cover highly dependent on the chosen window size. Variations in window size directly influenced the number of pixels meeting the building density and wildland vegetation cover thresholds. In contrast, our study employed building location without considering building density, thereby maximally preserving the building. FVC was obtained through the GF1 fusion images inversion. Our approach effectively mitigates the influence of varying window sizes, enhancing the spatial consistency of the WUI delineation.

(2) Parameter Threshold Differences

The distribution of the WUI is closely linked to the spatial characteristics of buildings and the FVC, which exhibit significant variations across different areas. Schug’s method employs a set of mainstream thresholds to delineate WUI on a global scale, and the applicability of these thresholds in Anning City remains uncertain. Generic thresholds may not accurately reflect local conditions due to the complex interactions between built structures and natural vegetation. We investigate appropriate thresholds for WUI delineation, incorporating vegetation distribution, building spatial characteristics, and their mutual interactions.

(3) Differences in the WUI Results

From the results of the WUI delineation (Figure 15), areas of overlap are mainly distributed in Lianran, Jinfang, Taiping, Wenquan, and Caopu, while notable discrepancies are observed in the northwest of Qinglong, the north of Wenquan, Lubiao, Bajie, and Xianjie. For instance (Bajie), the Schug’s results classify a substantial portion of farmland as WUI, and the vegetation area is small. Farmland is generally flat with limited fuel accumulation, whereas vegetated areas contain high biomass, abundant dead branches and fallen leaves, and rich combustible materials. In the event of a fire, vegetation areas are far more susceptible to fire. These vegetated regions should be prioritized in WUI fire management and mitigation efforts.

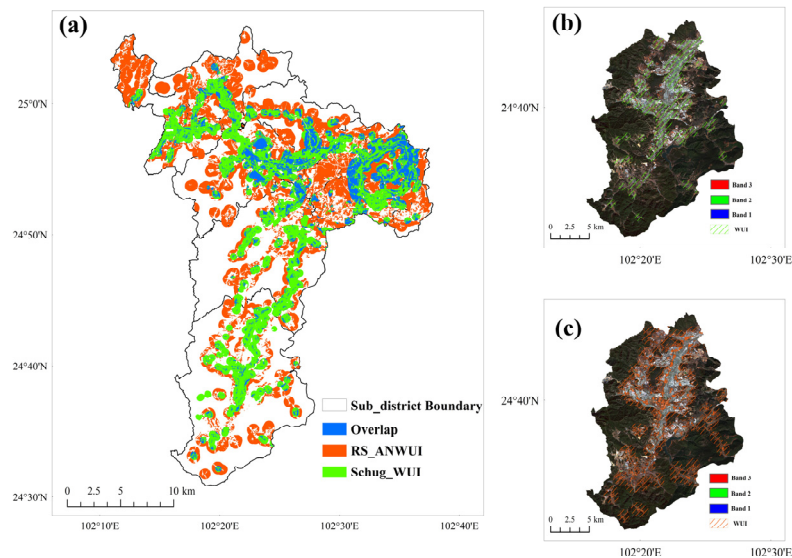


Figure 15. The distribution of WUI. (a) Overlap and difference between the results of the two mapping methods; (b) Bajie mapping results of Schug method; (c) Bajie mapping results of RS_ANWUI method.

The RS_ANWUI method mapped the area of WUI approximately 1.4 times larger than the Schug's (Table 4). For the differences, we conclude that the mapping purposes are distinctive in essence. Schug's method primarily aimed to safeguard the building side, while our goal considered both fire-affected buildings and the vegetation side. This perspective ensured a more comprehensive delineation of the WUI, accounting for both structural vulnerability and the role of vegetation in fire propagation. The clear separation of the building side and vegetation side certainly yielded a greater outward expansion compared with the convolution window.

Table 4. Comparative analysis of RS_ANWUI and Schug.

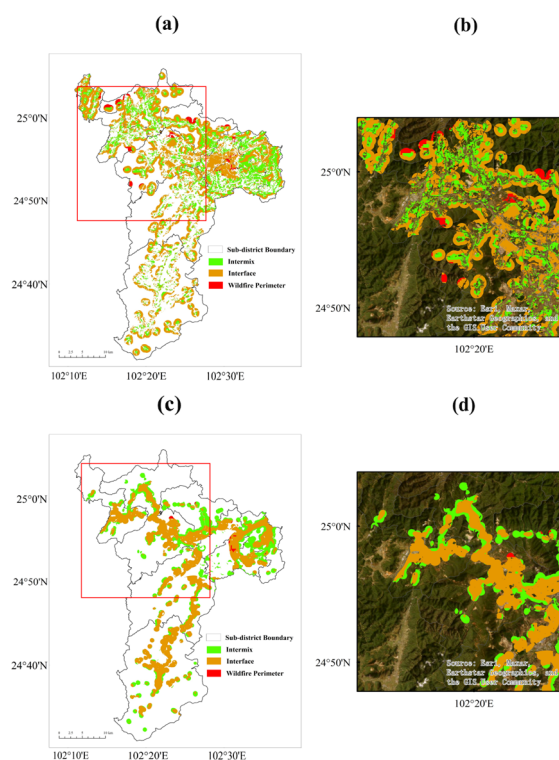
Method Name	Total Area of the WUI (ha)	Intermix Area(ha)	Interface Area(ha)	Percentage of Intermix to the City's Area(%)	Percentage of Interface to the City's Area(%)
RS_ANWUI	49,578.05	17,283.93	32,294.12	13.28	24.80
Schug	34,690.42	10,821.93	23,868.49	8.32	18.33

(4) Relevance to Fire Indicators

To confirm our map's usability in fire management, we compared the two sets of methods in their ability to reflect fire risk. The percentage of MODIS fire spots and the fire perimeter area appearing in the WUI were counted. Table 5 showed RS_ANWUI included 1115.95 ha fire perimeters, with 184.09 ha intermix fire perimeters and 931.86 ha interface fire perimeters. It was five times more than Schug's, which contained 196.59 ha. In regard to fire spots percentage, RS_ANWUI had a higher percentage of 33.86%, compared to Schug's 12.6%. Figure 16 presents the WUI and fire perimeters distribution in each method and reflects the discrepancy between the two mapping methods. The comparison here demonstrated our map was valid and could provide guidance for fire management in Anning City.

Table 5. The percentage of fire spots and the area of fire perimeters in two mapping methods.

Method Name	Percentage of Fire Spots in Intermix Area (%)	Percentage of Fire Spots in Interface Area (%)	Intermix Fire Perimeter (ha)	Interface Fire Perimeter (ha)
RS_ANWUI	6.30	27.56	184.09	931.86
Schug	3.15	9.45	35.6	160.99

**Figure 16.** The distribution of WUI and fire perimeter. (a) RS_ANWUI map, (c) Schug map. The detailed comparisons among these two maps of one selected enlarged region are shown in (b,d).

(5) Broader Applicability and Limitations of RS_ANWUI Method

Overall, the RS_ANWUI method combines GF1-PMS imagery characteristics and sensitivity analysis to optimize the parameter threshold in the WUI delineation of Anning City. The generalizability of the RS_ANWUI method can be illustrated from two perspectives.

On the one hand, the data sources are easily accessible. The rapid advancement of satellite technology in China provides a solid data foundation for the broader application of our proposed method. On the other hand, the zoning framework is transferable. In our methodology, we have clearly defined the zoning process. Although the generalizability of specific threshold values requires further validation, the zoning approach offers a valuable reference for future studies.

However, variations in vegetation coverage and building distribution among counties in China necessitate further validation of whether the derived threshold parameters are applicable to other county-level. To enhance the universality of the RS_ANWUI method, the number of study areas can be expanded. In future work, researchers could apply this framework at the provincial or national scale, and refine it by incorporating the Local Climate Zones.

5. Conclusions

This study employed the 2 m fused GF1 imagery to extract buildings and estimate FVC. The buildings and FVC were used as mapping inputs. Overall, our conclusions can be summarized into three aspects.

(1) Methodological Contribution

The dual-perspective approach marks a methodological advance over traditional WUI mapping techniques. Traditional techniques only considered the building perspective. In our method, we also added a vegetation perspective, and provided an innovative perspective in WUI mapping.

The integration of “GF1 + WUI” expands the application fields for high-resolution remote sensing imagery and improves the WUI map’s resolution. Anning’s WUI was mapped using a set of data sources, whereas other researches were derived from different datasets. The spatial resolution of the WUI map improved to 2 m, compared with Schug’s 10 m.

(2) The Applicability in Anning City

The method was well-suitable for Anning City. Firstly, the threshold parameters were established in consideration of the specific characteristics of Anning City. Second, the overall classification accuracy of the WUI is 88.56%, with an F1-score of 0.88 for the intermix area, 0.87 for the interface area, and 0.91 for the non-WUI. WUI mapping methodology was trustworthy. Moreover, the threshold of the RS_ANWUI method in other county-level regions remains to be validated.

(3) Suggestions for Future Work

We used the buildings and the vegetation to develop a WUI mapping method, and formed a basic mapping process. The basic framework could provide a reference for the WUI mapping in other areas. A new threshold was suggested to refine by integrating climate, fire modeling, or socio-economic vulnerability layers. From the relationship between fire spots and WUI distribution, fire-prone sub-districts overlapped with those that had a larger WUI area. In WUI fire risk zoning, WUI distribution is recommended as a factor.

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