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Planning to Practice: Impacts of Large-Scale and Rapid Urban Afforestation on Greenspace Patterns in the Beijing Plain Area

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Abstract: (1) Research Highlights: Afforestation is one of the most effective urban greening practices for mitigating a variety of environmental issues. Globally, municipal governments have launched large-scale afforestation programs in metropolitan areas during the last decades. However, the spatiotemporal dynamics of urban greenspace patterns are seldom studied during such afforestation programs. (2) Background and Objectives: In this study, the Beijing Plain Afforestation Project (BPAP), which planted 70,711 ha of trees in only four years, was examined by integrating spatial and landscape analysis. To evaluate the real-world outcomes of this massive program, we investigated the spatial-temporal dynamics of landscape patterns during the implementation process to identify potential impacts and challenges for future management of new afforestation. (3) Materials and Methods: We analyzed the transition of various patch types and sizes, applied landscape indicators to measure the temporal changes in urban greenspace patterns, and used the landscape expansion index to quantify the rate and extent of greenspace spatial expansion. (4) Results: Our results illustrated that the implementation of afforestation in the Beijing plain area had generally achieved its initial goal of increasing the proportion of land devoted to forest (increased 8.43%) and parks (increased 0.23%). Afforestation also accelerated the conversion of small-size greenspaces to large-size patches. However, the significant discrepancies found between planned and actual afforestation sites, as well as the large conversion of cropland to forest, may present major challenges for project optimization and future management. (5) Conclusions: This study demonstrated that spatial analysis is a useful and potentially replicable method that can rapidly provide new data to support further afforestation ecosystem assessments and provide spatial insights into the optimization of large inner-city afforestation projects.

Keywords: inner-city greening; forest and trees; transition detection; landscape metrics; landscape expansion; city ecosystems

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1. Introduction

Urban greenspace, i.e., area of trees, shrubs, grasses, or other vegetated area [1], has been investigated for its contribution to biodiversity conservation and human livability in high urban intensity areas [2–4]. Urban forests and trees are important for relieving summer heat waves, soil contamination, as well as air and water pollution [5–7], and provide recreation space for city residents and food and habitats for animals (e.g., birds, butterflies and bees) [8–10]. Thus, the loss of urban trees, forest, and vegetation can impact urban ecosystems and human well-being [11,12].

Urbanization and the subsequent population expansion and land use/cover changes have resulted in rapid forest clearing or deforestation both regionally and globally [13–

16]. In the past three decades, deforestation has greatly threatened urban biodiversity [17–19], ecosystem services [20,21] and the health of humans and wildlife [22], also having negative impacts on the urban soil [23], urban water cycle [24] and atmosphere [25], leading to effects such as soil erosion, flooding, and urban heat islands [26,27]. Under the pressure of such environmental issues, fighting deforestation has become a crucial task for municipal governments. Thus, greening and renaturing urban areas have been implemented across the world [28,29].

Afforestation is one of the major practices for city ecological restoring and regreening [30,31], converting non-vegetated areas to forest land through planting trees [32,33], playing an important role in mitigating environmental degradation [13,34] e.g., increasing urban greenspace and improving soil fertility [35], increasing the habitat for urban animals, and regulating urban climates [32]. Globally, over 40 countries have invested at least 15% of their government revenue to national forest conservation, afforestation, reforestation, and plantation [36]. Owing to these efforts, a regional increase in vegetation indices such as the Normalized Difference Vegetation Index and the Enhanced Vegetation Index has been widely reported in recent years [20,37–40].

As one of the most rapidly urbanizing countries worldwide [41], China has seen an average of 9.71% gross domestic product growth every year since 1989 [42], and accommodates 19% of the global population [43], while facing serious environmental issues such as air and water pollution and land degradation. Within this context, the government has made great efforts to implement multiple environmental programs to control rising ecological problems. Since 1979, China has launched several afforestation programs, such as the Nature Forest Conservation Program, the sloping land conversion program [44], the "Three North" Shelterbelts Program, and Beijing-Tianjin Shelterbelt Program, planting over four million hectares of trees per year [45]. These afforestation programs enhance the proportion of vegetation and are beneficial for ecosystems, e.g., reducing greenhouse gas emission and cooling the local surface temperatures [43,46–48]. However, although landscape configuration and composition are closely related to biodiversity, habitats, and livability [49], few studies have focused on the real-world effects of afforestation on landscape patterns (e.g., patch-corridors-matrix).

The type, size, and connectivity of greenspace patches have direct impacts on the foraging, migration, and breeding of birds, bees and many other animal communities [10,50,51]. The size and spatial characteristics of greenspaces are also related to ecosystem services such as cooling effects, food supplies, and human recreation [52,53]. For example, greenspaces with large area and compact spatial distribution can enhance their cooling benefits [54,55], and increasing greenspace patch size can increase the species richness of birds and bees [56,57].

Given the importance of greenspace patterns for landscape benefits and ecosystem services, various landscape ecological methods, principles, and models have been applied to aspects of urban afforestation, greenspace design, and planning [58], e.g., the pattern-process principle, metapopulation theory, and network-based approaches [59]. Nevertheless, it is usually not clear if these plans or guidelines have been well executed during implementation (e.g., identifying whether trees were planted as planned), as most related studies focus on the long-term trends of landscape patterns [32,35,60], and planners or decision-makers have not used landscape ecological analysis to track where and how their planning schemes have been implemented in the short-term [61,62]. In addition, unlike the assessment of ecosystem services such as heat island mitigation, carbon sequestration, and water purification, which need a relatively long time to emerge if provided by newly planted forests, changes in landscape patterns often rapidly reflect the outcomes of such greening projects. Therefore, it could be advantageous to identify and monitor the landscape pattern dynamics before, during and soon after specific afforestation programs, which would allow decision makers and planners to reorient or optimize these large and costly ongoing projects.

Several indices have been developed to measure the heterogeneity characteristics of landscape patterns at multiple scales, such as aggregation, diversity, size, edge, and shape metrics, which have been widely used in large-scale landscape pattern studies [63,64]. In addition, some new landscape indicators (e.g., surface metrics) have been created to quantify landscape connectivity, patch expansion, and ecological process [65–67], providing a promising method for quantitative research and spatial analysis of afforestation pattern changes. However, most landscape metrics show interactions and can be difficult to interpret [68]. Therefore, it is important to select or integrate suitable metrics for specific research on landscape pattern changes.

As the capital of China, Beijing has implemented considerable tree planting and forest management practices since the 1940s [47,69]. However, the city is still experiencing conflicts between urban greenspace expansion and urban sprawl in recent years. In the last two decades, the plain area in Beijing has experienced rapid urbanization and faced serious environmental degradation such as deforestation of urban forest [70], air pollution [71], and heavily exploited groundwater [72]. The greenspace system in the plain area has three major problems: (1) the percentage of forest cover in the plain area is 36% less than that in mountainous areas (Figure 1); (2) small and fragmented forest patches are dominant in the plain area; and (3) community greenspace is failing to meet the demands of residents, e.g., some residents have to drive 40–50 km if they want to visit a forest park [29,70]. To mitigate these environmental pressures and improve urban sustainability and resilience, the municipal government in Beijing has launched various afforestation programs since 2000 (e.g., two greenbelt programs during 1993 and 2010). Among them, the Beijing Plain Area Afforestation Project (BPAP) has been considered as the most ambitious greening program in the high-density urbanized area. With the aim to "create huge forest patches, develop urban forest park clusters, and optimize the large-scale forest patterns" [73], BPAP has proposed green strategies with "greenbelts", "green wedges", "green rings", and "green corridors" around the old city center (Figure 1). The BPAP planned to plant 66,674 ha of new forests by converting vacant lots, croplands, sand excavation pits, and wastelands to forests, parks, and wetlands from 2012 to 2015 [74]. Considering the ecological criteria such as being native, drought-tolerant and longevity, a total of 37 tree species (e.g., *Pinus tabuliformis Carr.*, *Sophora japonica Linn.*, *Populus spp.*, *Salix spp.*, *Ginkgo biloba L.*, *Fraxinus chinesis Roxb.*, etc.) were officially recommended for the plain afforestation. During the implementation of BPAP, the proportion of native tree species reached 91.97% [75]. By the end of 2015, BPAP increased plain forest coverage to 25%, and 54 million trees (the survival rate has exceeded 95%) had been planted in the plain area [76]. Therefore, BPAP provides a valuable field site to study the cycle of city afforestation from planning to practice and identify how the landscape heterogeneity changes during the implementation progress.

This research aims to integrate multiple landscape metrics and spatial analysis to quantify the continuous changes of landscape patterns during BPAP implementation, and to assess whether BPAP optimized urban forest patterns in the Beijing plain area as originally intended. For example, does this project plant the new trees in the planned area; whether the afforestation sites are selected as designed and what are the potential impacts of landscape changes on urban ecosystems. Thus, our study can be considered as a first step toward the further assessment of ecosystem services and other costs or benefits. The objectives of our study were to (1) examine and visualize the spatial-temporal dynamics (including landscape transitions and expansion) of landscape patterns changed by BPAP, to (2) identify the positive or negative effect of this large-scale inner-city afforestation, and to (3) clarify potential challenges of future management for new afforestation. Taking the Beijing plain region as our study area, we used GIS-based change detection technology to demonstrate the transition and interactions of various landscape mosaics, and applied seven common landscape metrics as well as landscape expansion index (LEI) to investigate the characteristics and changes of landscape composition, configuration, and expansion during BPAP implementation [77]. Such results may expand the understanding of city afforestation from planning to practice, and provide specific spatial insights for the optimization and future full assessment of ecosystem services in such urban greening projects.

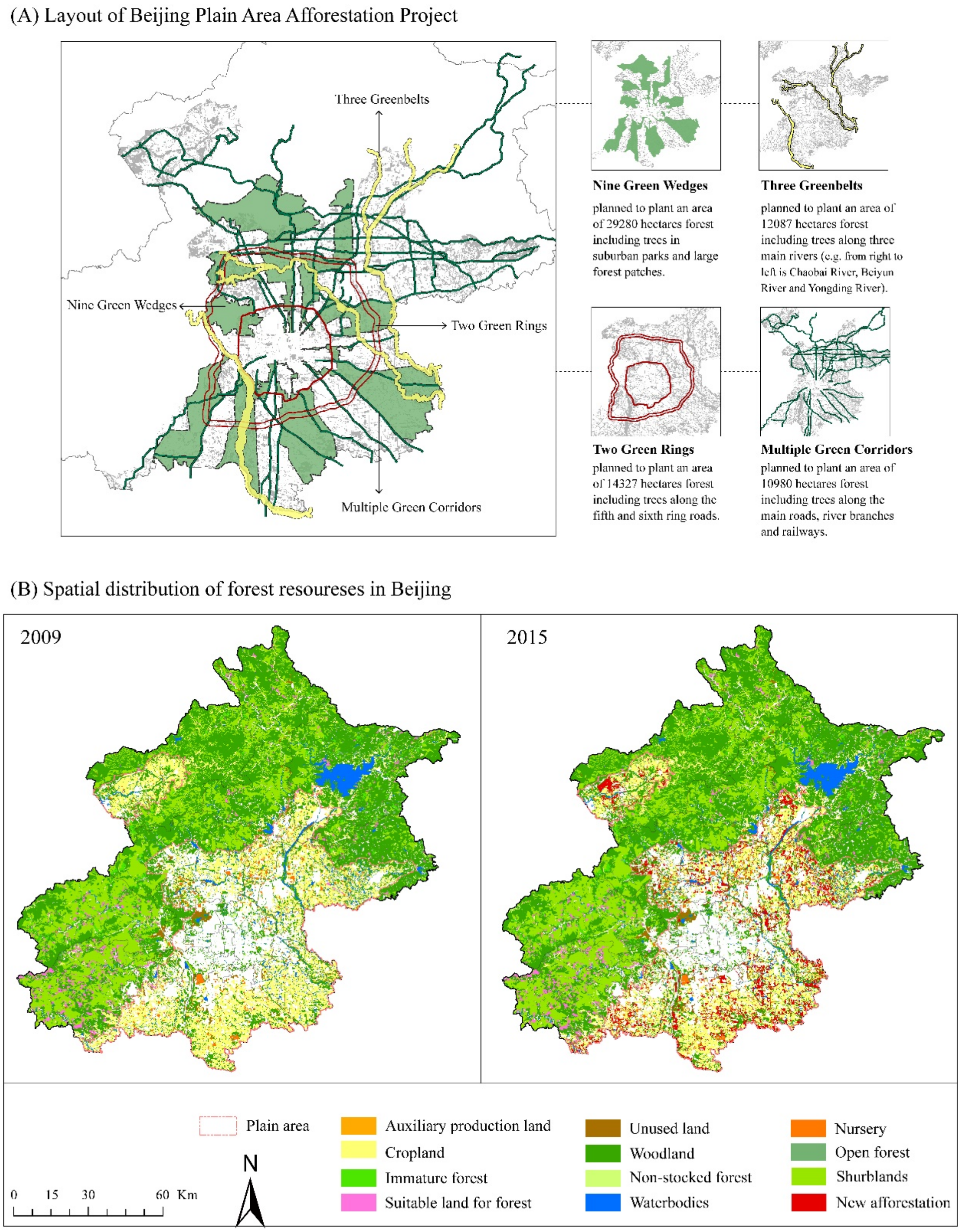
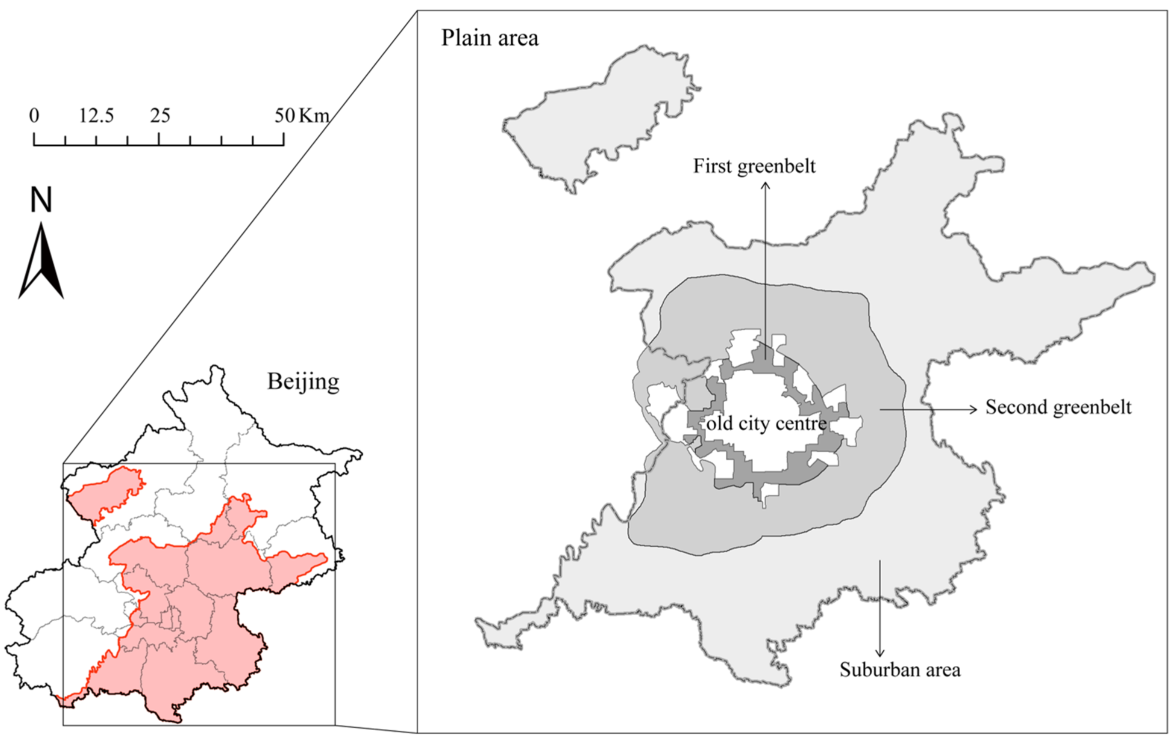


Figure 1. (**A**) Layout of Beijing Plain Area Afforestation Project (BPAP). The left panel showed the sketched BPAP map, which consisted of four green strategies [74]; the gray polygons referred to the urban greenspace in 2009. The right panels showed the planning objectives of four green strategies (i.e., green wedges, greenbelts, green rings, and green corridors). All BPAP data are from Beijing Gardening and Greening Bureau. (**B**) Spatial distribution of forest resources in 2009 and 2015. The new afforestation indicates the new trees planted during the implementation of BPAP.

2. Material and Methods

2.1. Study Area

Beijing is located in the north of China and has a metropolitan area of 16,400 km^2, consisting of 16 districts. With a size of 6596 km^2, Beijing's plain area encompasses the entire city central and the most recently expanded urban areas (Figure 2), housing over 70% (nearly 16 million people) of Beijing's population [78]. In this study, we used the division methods for Beijing described in Pan's research [79], which divides Beijing's plain area into the old city center, the first greenbelt, the second greenbelt, and the suburban area (Figure 2). Beijing shows a concentric zone model of urban growth, with the Forbidden City being the center and the urban built-up areas expanding outward concentrically. The urban area has been broken down into six concentric circles called the "six ring roads" [80]. According to the 2004–2020 Beijing Master Plan, the region inside the sixth ring road is classified as an urban district, and the area encircled by the fifth ring road is regarded as the central city [81]. To control urban expansion, the local government implemented two greenbelt programs in 2000. The first greenbelt is the area encircled by the fourth and fifth ring roads, and the second greenbelt is encircled by the fifth and sixth ring roads [82]. The old city center is the region encircled by the fourth ring road, with higher population density than that of other sub-regions [83].



Sub-regions	Location	Area (Km^2)	Non-forest land (%)
Old city centre	Encircled by the fourth ring road	507	93.33
First greenbelt	Between the fourth and fifth roads	256	67.82
Second greenbelt	Between the fifth and sixth roads	1531	73.09
Suburban area	Outsize the sixth road	4302	75.84
Plain area		6596	77.51

Figure 2. Plain area location and sub-regions. Proportion of non-forest was based on the Beijing Forestry Inventory (2009), and the non-forest land included cropland, other land, unused land, and waterbodies [84].

2.2. Spatial Data Collection and Preprocessing

We collected Beijing's geographic data (including administrative boundary, elevation, and sub-region borders), Beijing Forestry Inventory database (BFI, 2009), Beijing Urban Park Inventory database (BUPI, 2009), wetlands census data (2010), and the BPAP geodatabase (2012–2015) from Beijing Gardening and Greening Bureau and Beijing Forestry Survey and Design Institute [85,86]. The BPAP database is created based on a series of high-resolution remote sensing images through visual interpretation and annual field inventory validation with an average accuracy of 90%. The landscape is spatially complex and is viewed as an assemblage of various patch types [87]. In this study, categorical data from BFI, BUPI, wetlands, and BPAP databases [88] were combined to reclassify eight patch types (Table 1) using ArcMap 10.5 [89].

Table 1. Patch mosaics created by the categorical datasets from Beijing Forestry Inventory database (BFI, 2009), Beijing Urban Park Inventory database (BUPI, 2009), wetlands census data (2009), and the geodatabase of Beijing Plain Afforestation Project (BPAP, 2012–2015).

	Patch Types	Description	Database
Urban green-space	Forest	Including coniferous forests, broad-leaf forests, mixed forests, national protective forests, other shrublands, young afforested lands, enclosed young afforested lands [90], auxiliary production forest lands, and the new forest area	BFI, BPAP
	Parks	Parks	BUPI, BPAP
	Wetlands	Wetlands	Wetlands census data, BPAP
	Vacant lots	Land suitable for afforestation [91], including cut-over forest, burned forest and other non-stocked forest	BFI
Other space	Croplands	Cropland	BFI
	Waterbodies	Waterbody	BFI
	Other land	Including all urban built-up area and other impervious area	BFI
	Unused land	Unproductive non-forest land or lands are not suitable for afforestation	BFI

2.3. Landscape Transition Detection

To identify and describe the conversion of landscape types and their patch size, a landscape transition matrix was used to measure the amounts of different patch types and their size changes in corresponding period (i.e., 2009−2012, 2012−2013, 2013−2014, 2014−2015) [92]. To detect the growth of greenspace patch size, we divided the patch size into six levels: (1) very small, (2) small, (3) medium, (4) large, (5) very large, and (6) huge (<10, 10–30, 30–50, 50–100, 100–200, >200 ha, respectively) before creating the patch-size transition matrices [53,93]. As the total number of greenspace patches varied among periods, and thus the total landscape areas (i.e., the number of pixels in the maps) were different, we detected the transitions in the proportion of land area for each patch-size class instead. Finally, a Sankey diagram was used to visualize the four-period transition matrices of landscape types and greenspace patch size from 2009 to 2015 [94]. Sankey diagrams were created using the networkD3 package in RStudio 3.6.1 [95].

2.4. Spatial Pattern Analysis

To examine the changes in landscape patterns after BPAP, we calculated seven class-level and one landscape-level metrics using Fragstats version 4.2 [96]. Percentage of landscape (PLAND) and number of patches (NP) were chosen to measure landscape composition, as they can quantify the amount and dispersion of the corresponding patch mosaics [97,98]. The increased PLAND and NP values indicate the area of corresponding patch type rises in the landscape. If the total landscape area and class area are constant, a higher NP value indicates a higher fragmentation. Mean patch size (MPS), contagion index

(CONTAG), and area-weighted mean shape index (AWMSI) were used to characterize the fragmentation and shape complexity of landscape patterns [77,96]. The increased MPS value indicates the spatial distribution of corresponding patch types become less fragmentation. An increased CONTAG value indicates all patch types become more aggregated in the landscape. A higher AWMSI value indicates the shape of corresponding patch types turn more irregular. To further understand how afforestation changed the spatial patterns from the city center to the suburbs, we applied five landscape metrics in the entire plain area and in three sub-regions. Dot plot was created to visualize the changes of landscape metrics by using the ggplot2 package in RStudio 3.6.1 [99]. All the selected landscape metrics were listed in Table 2.

Table 2. List of selected landscape metrics from Fragstats version 4.2 [96,98].

Abbreviation	Landscape Metrics	Unit	Range	Explanation
PLAND	Percentage of landscape	Percent	0% < PLAND < 100%	Proportion of the corresponding patch type in total landscape
NP	Number of patches	None	NP ≥ 1, without limit	It measures the division of the corresponding patch type. Increased NP in the constant landscape area refers to increased fragmentation
MPS	Mean patch size	Hectares	MPS > 0, without limit	It measures the fragmentation of the corresponding patch type. Increased MPS in a constant landscape refers to decreased fragmentation
AWMSI	Area-weighted mean shape index	None	AWMSI ≥ 1, without limit	It measures the complexity of patch shape. Higher AWMSI indicated more irregular patches
CONTAG	Contagion index	Percent	0% < CONTAG ≤ 100%	It measures the fragmentation of total landscape and is related to the interspersion of patches. A higher CONTAG refers to a less fragmented landscape with relatively large patches

2.5. Greenspace Expansion Analysis

Landscape expansion, as one of the ecological processes, have great effects landscape patterns [49]. To link the landscape patterns with process, we analyzed the patterns of greenspace expansion during the afforestation implementation. Three landscape expansion models (i.e., infilling, edge expansion, and outlying; Figure 3) were used to discern the patterns of greenspace growth. We then calculated Landscape Expansion Index (LEI) using the LEI tool created by Liu to quantify the expansion modes [67,87]. In addition, considering the greenspace accessibility, species movement distances, and cooling efficiency of urban heat mitigation, we chose buffer with 240 m around the pre-existing greenspace when calculating LEI [49,100–102]. As the afforestation program started in 2012 and ended in 2015, we calculated and mapped LEI of greenspace in four periods (i.e., 2009–2012, 2012–2013, 2013–2014, and 2014–2015). We further calculated the percentage of the three landscape expansion types in each period. The greenspace expansion analysis was conducted in ArcMap 10.5 [89].

$$Landscape\ expansion\ index\ (LEI) = \frac{Area_b}{Area_b + Area_v} \tag{1}$$

where $Area_b$ was the intersection area between the buffer and corresponding patch type, and $Area_v$ was the intersection area between the buffer and vacant area. *LEI* ranged from 0 to 1.

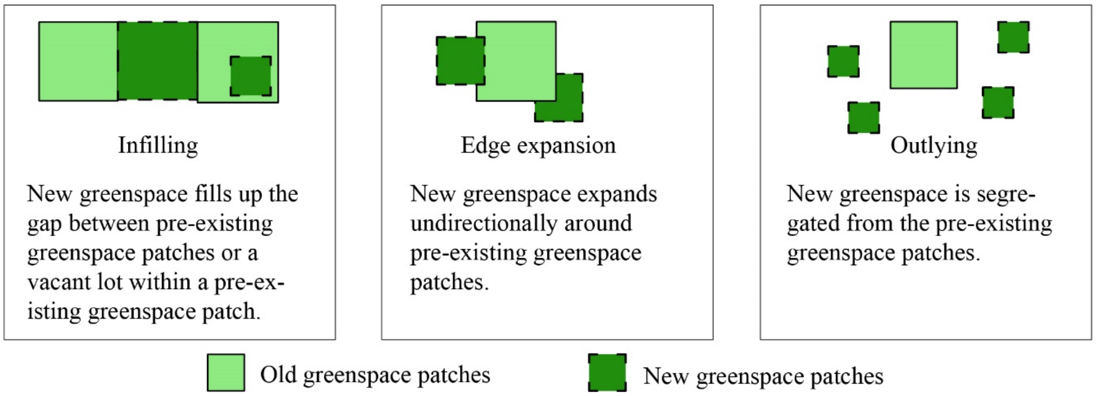


Figure 3. Diagrammatic illustration of three landscape expansion models adapted from Forman and Liu [67,87]. The greenspace expansion belongs to infilling, edge expansion, and outlying mode when LEI ≥ 0.5, < 0.5, and 0, respectively.

3. Results

3.1. Afforestation Increased the Overall Forest in Plain Area, Exceeding the Original Goal

A GIS-based comparison of the newly grown greenspace and planned afforestation area showed that, after afforestation, the total newly grown greenspace fulfilled the planned goal, exceeding it by 4037 ha of trees (Table 3). Regarding the four green strategies, only “Nine green wedges” and “Multiple green corridors” achieved the initial planned goals and exceeded them by 861 and 3081 ha, respectively. In addition, areas that were not included in the four “green strategies” gained 17,266 ha of new greenspace. Overall, BPAP accomplished and even exceeded the target of total planned area although the greenbelts and green rings were not completed.

Table 3. Planned new greenspace area and actual new greenspace growth area after the implementation of afforestation. “YES” and “NO” indicated an actual greenspace growth area over and under the planned area, respectively; while “NEW” indicated new greenspace growth not included in the master planning.

Green Strategies	Planned Area (ha)	Actual Growth Area (ha)	Achieved (ha)
Nine green wedges	29,280	30,141	YES
Three greenbelts	12,087	6,331	NO
Two green rings	14,327	2,962	NO
Multiple green corridors	10,980	14,011	YES
Other area	-	17,266	NEW
Total	66,674	70,711	YES

3.2. Afforestation Accelerated Substantial Cropland Conversion to Forest and Growth of Greenspace Size

The stacked bars in the Sankey diagram (Figure 4) represented the relative proportion of patch mosaics, showing that other lands (including urban built-up areas and other impervious surfaces) followed by cropland were the dominant patch type in the plain area, with an area decreased by 1.13% and 6.77% from 2009 to 2015, respectively. Forest was the third most dominant patch mosaic, and its area increased by 8.43% after afforestation, with the largest annual increase in urban forest area occurring between 2012 and 2014. Specifically, the transition rates of forest area reached 14.94% and 12.73% in the period of 2012–2013 and 2013–2014, respectively (Appendix A, Table A1). After BPAP implementation, parks showed a minimal increase (0.23%), while wetlands decreased (0.36%). The area of waterbodies and vacant lots slightly decreased from 2009 to 2015 (0.08% and 0.02%, respectively).

The flow lines in the Sankey diagram (Figure 4) showed the transition from cropland having the greatest contribution to the increased urban forests (19.93% of cropland converted to urban forest after BPAP implementation). This, together with small contributions from other patch types (other lands, vacant lots, waterbodies, and unused land), resulted in an urban forest expansion from approximately half the cropland area in 2009 to an area roughly equal to that of cropland (the proportion of forest and cropland in 2015 are 24.55% and 25.21%, respectively) in only seven years (Figure 4).

Figure 4. Sankey diagram for patch mosaic transition in the entire plain area in 2009 (before afforestation), 2012, 2013, 2014, and 2015. Stacked vertical bars with different colors indicated the relative area proportion for each patch type, i.e., percentage of landscape (PLAND), in the corresponding year. Grey flows between stacked bars showed the patch type transitions from one year to the next, with width indicating the transition percent between two patch mosaics. The proportion (%) of each patch type in the total landscape in each year was also labeled. The corresponding four period landscape transition matrices can be found in Table A1.

Considering all urban greenspace patches, the total area of forest, parks, wetlands, and vacant lots together grew from 25.4% to 34.68% of the total plain area (Figure 4). Throughout the seven years, the flow lines in the Sankey diagram (Figure 4) also showed the transitions among greenspace types. For example, some forests were converted to parks and wetlands, while parks, vacant lots, and wetlands were transformed into forests (e.g., 564.68 ha forests converted to parks and 88 ha vacant lots changed to forests; Table A1). Generally, both forests and parks continuously increased, while wetlands showed a slight decreasing trend throughout the afforestation process.

In addition to overall land proportions, the transition in patch sizes partly owing to afforestation needs to be understood. The stacked bars in the Sankey diagram (Figure 5) illustrated the relative proportion of greenspace land areas for each patch-size category. Generally, the proportion of the land area of very-small (patch size <10 ha), small (10–30 ha), and medium (30–50 ha) patch classes showed declining trends in four periods during BPAP implementation, which is contrary to the results for large (50–100 ha) and huge (> 200 ha) patch classes. The huge patch class area was predominant in all five years and showed an increasing trend during the afforestation process, comprising 33.51% of total greenspace landscape area in 2009, and increasing to 38.05% in 2015. However, the very-small patch class, as the second dominant category, presented a distinct decreasing trend from 2009 to 2015 (decreased by 3.55%). Despite the overall increasing trend, the proportion of very-large (100–200 ha) patches slightly decreased from 2013 to 2014 (0.08%).

Figure 5. Sankey diagram of patch size class transition for urban greenspace (including forest, parks, wetlands, and vacant lots) in 2009, 2012, 2013, 2014 and 2015. The stacked vertical bars with different colors indicated the relative proportion of each patch size class in the corresponding year. The grey flows between stacked bars showed the different patch size class transitions, with the width representing the transition percent between two size classes. The proportion (%) of land area of each patch size class in the corresponding year was also labeled. The corresponding four period patch size transition matrices can be found in Table A2.

The flow lines in the Sankey diagram showed that smaller greenspace patches have been converted to larger sizes in the process of afforestation (Figure 5). Specifically, the transition of very-large patches had the greatest impact on the expansion of huge patch sizes through afforestation, while most large patches were expanded to very-large patches (the land area proportion change for each patch size class can be found in Table A2).

3.3. Afforestation Enhanced Forest Aggregation

The changes in forest, cropland, and other land were more distinct than those of other patch types (Figure 6). To further understand the changes in landscape patterns after afforestation, we first focused on the urban greenspace categories, i.e., forest, parks, wetlands, and vacant lots. Regarding landscape composition, i.e., percentage of landscape (PLAND), forests showed the largest change after afforestation (Figure 6). Regarding the changes in sub-regions (first greenbelt, second greenbelt, and suburban area in Figure 6b–d, respectively), forest showed an increasing growth outward from the first greenbelt. The first greenbelt showed the largest decline in parks, while the second greenbelt showed the highest wetland decline and park growth. Specifically, forest PLAND increase in the suburban area (10.22%) was larger than those in the first and second greenbelt (increase by 2.4% and 6.22%, respectively), indicating that most new forests were located in the outskirts; urban parks PLAND had the highest increase in the second greenbelt (0.95%), while it showed a decrease of 0.37% in the first greenbelt.

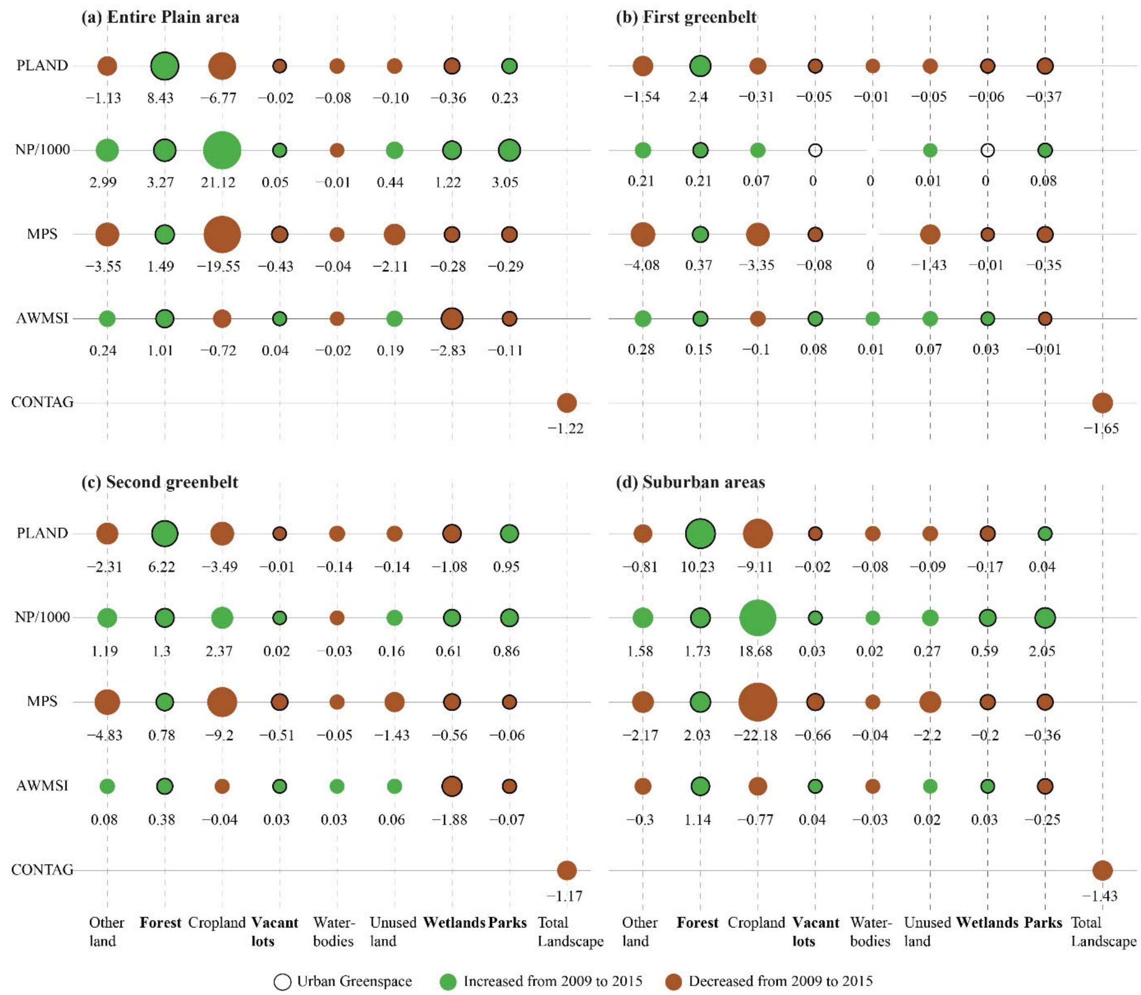


Figure 6. Changes in class-, i.e., percentage of landscape (PLAND, an increased value indicates the relative increased area of corresponding patch type), number of patches (NP, if the total area of corresponding patch type is held constant or decreasing, an higher value indicates higher fragmentation), mean patch size (MPS, an increased value indicates less fragmentation), area weighted mean shape index (AWMSI, an increased value indicates the patch shapes become more irregular), and landscape-level, i.e., contagion (CONTAG, an decreased value indicates the distribution of all patches become more fragmented), indices from 2009 to 2015 in the entire plain area (**a**), the first greenbelt (**b**), the second greenbelt (**c**) and the subregion area (**d**). The vertical and horizontal axes indicated the landscape indices and patch types, respectively; dot size represented the absolute value of change; green and brown indicated increase and decease, respectively, while white indicated no change from 2009 to 2015; dots with black outlines indicated urban greenspace (i.e., forest, parks, wetlands, vacant lots). The value of change was indicated below each dot.

Despite the increased fragmentation of the entire plain landscape, i.e., contagion (CONTAG) decreased, greenspace (e.g., forest, parks, and wetlands) presented different fragmentation trends, i.e., mean patch size (MPS) and area weighted mean shape index (AWMSI) (Figure 6). Considering landscape configuration, forest patterns became more connected in the entire plain and the three sub-regions (Figure 6). Specifically, forest patterns became more aggregated (MPS increased 1.49), while those of parks, wetlands, and vacant lots showed higher fragmentation (MPS decreased 0.29, 0.28, and 0.43, respectively) after afforestation in the entire plain area. These changes also occurred in the three sub-regions (Figure 6). In contrast to that of parks and wetlands, the shape of forest and vacant lot patches became more irregular (AWMSI increased by 1.01 and 0.04, respectively) as AWMSI increased in the entire plain area and the second greenbelt (AWMSI increased by 0.38 and 0.03, respectively). In the first greenbelt and suburban area, only the shape of park patches increased in regularity with afforestation (AWMSI decreased 0.01) contrasting with those other greenspace types (forest, wetlands, and vacant lots).

The proportion of other landscape patch types (other land, cropland, waterbodies, and unused land) decreased in the entire plain area as well as in the three sub-regions (Figure 6). Other land and cropland showed changes in landscape metrics more distinct than those of waterbodies and unused land. Additionally, the patterns of other landscape patch types became more fragmented in the entire plain and the three sub-regions after afforestation. With afforestation, other land AWMSI increased by 0.24, 0.28, and 0.08 in the entire plain area and the first and second greenbelt, respectively, indicating that the shape of other land patches, except those in suburban areas, became more regular. In contrast, the shape of cropland patches became more irregular after afforestation in the entire plain area and the three sub-regions (AWMSI decreased 0.72, 0.1, 0.04, and 0.77, respectively). Meanwhile, the shape of waterbody patches became more irregular in the entire plain area and suburbs, and unused land showed the opposite trend. However, both of them increased regularity after afforestation in the two greenbelts.

3.4. The Infilling Greenspace Expansion Type Increased During Afforestation

Edge expansion (new greenspace expanding peripherally around the pre-existing patches) was the most common greenspace expansion type during the afforestation (Figure 7). Throughout all afforestation periods, edge expansion accounted for over 69% of the three greenspace expansion types. With BPAP implementation, the proportion of outlying and edge expansion types decreased, while the infilling type increased. Specifically, from 20092012 to 2012–2013, the infilling percentage increased by 2.87%, while the outlying and edge expansion percentage decreased by 0.05% and 2.81%, respectively. From 2012–2013 to 2013−2014, the infilling percentage increased by 2.89%, while the outlying and edge expansion percentage decreased by 0.99% and 1.91%, respectively. From 2013–2014 to 2014–2015, the infilling percentage increased by 5.21%, while that of outlying and edge expansion decreased 4.95% and 0.24%, respectively. The largest infilling increase occurred during 2013 and 2015, the last two afforestation years.

Regarding the spatial distribution of greenspace expansion, most infilling (red color) was distributed along the rivers and roads, and located in the suburban areas (Figure 7). Specifically, most new infilling greenspaces were distributed along the Yongding River (located in the south of the plain area) and Beiyun River (located in the northeast of the plain area) in 2009–2012, 2012–2013, and 2013–2014. In 2014–2015, most infilling greenspaces were distributed in the southeast of the plain area.

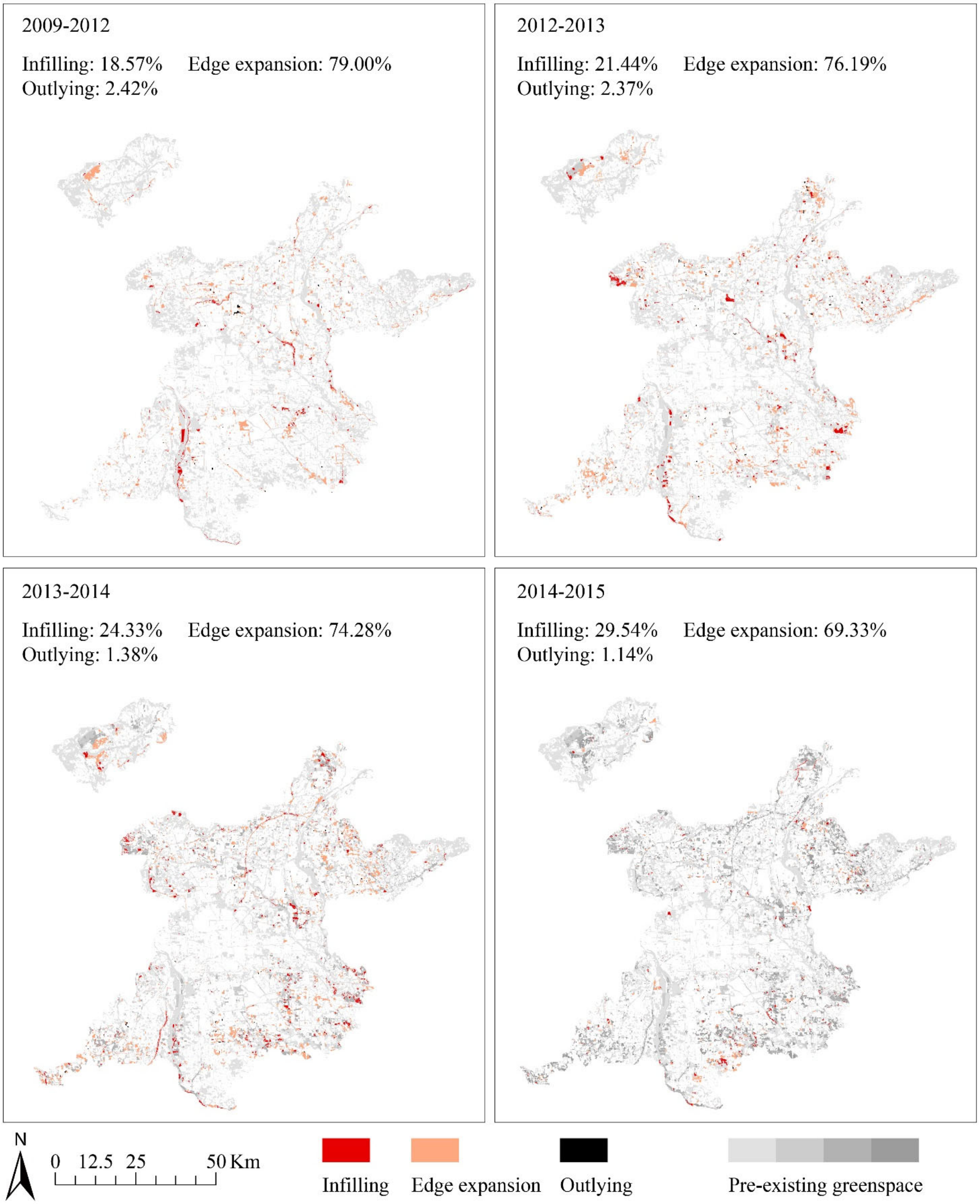


Figure 7. Maps of urban greenspace landscape expansion types (i.e., infilling, edge expansion, outlying) in 240 m distances during the process of afforestation in 2009–2013, 2012–2013, 2013–2014, 2014–2015. The proportions of each landscape expansion type were also listed on the top of each panel.

4. Discussion

4.1. Potential Impacts of Inner-City Afforestation on Urban Ecosystems and Inhabitants

Our results indicated that BPAP improved the proportion of greenspace (especially forest) and accelerated the transition from small to large greenspaces, enhancing the green network connectivity in four years (from 2012 to 2015). This further confirmed that large-scale inner-city afforestation plays an important role in the enhancement of greenness in metropolitan areas [60,103]. As the quantity, size, and spatial arrangement of greenspace are essential for urban biodiversity and human health, afforestation will benefit both humans and animals in urban areas [104–107]. Specifically, the increased forest patches provide additional habitats for urban wildlife, and the decreased fragmentation as well as increased patch size and complexity patch shape also are expected to have positive impacts on species composition, richness, and their movement [13,108,109]. Moreover, the extended and aggregated greenspace is expected to enhance cooling effect benefits by increasing canopy cover and evapotranspiration [7,53,110]. For human well-being, the increase in nearby greenspaces can mitigate air pollution and provide more recreation sites and equitable access for residents, which are beneficial for human mental and physical health [111]. Contrasting with forests and parks, other land (i.e., urban built-up area and impervious surfaces) showed an apparent decline in the first and second greenbelt and suburban areas after BPAP implementation. This indicated that afforestation has enhanced the two previous greenbelt programs [82] and relatively controlled the disordered urban sprawl outward from the old city center.

The changes in greenspace patterns suggests several positive effects through the implementation of afforestation. However, the massive new forests and trees might lead to potential negative impacts on the urban thermal and ventilation environment. Afforestation will lead to a net warming if the daytime cooling is unable to offset the warming during nighttime [48]. In addition, the huge amounts of new trees may reduce wind speed and mixing heights, which could exacerbate air pollution [112]. New afforestation also produces more pollen and catkins, which may threaten sensitized people (e.g., allergies), as large amount of *Pinus tabulaeformis Carr.*, *Ginkgo biloba L*, *Salix spp.*, *Populus spp.*, and *Platycladus orientalis* had been planted during BPAP [75,113,114]. Thus, based on our study, a detailed assessment of ecosystem services after afforestation is still needed: for example, linking the greenspace spatial patterns to specific tree species and community locations to analyze the phytogenic pollution risks, and connecting greenspace heterogeneity with surface or air temperatures to investigate the interactions between new afforestation sites and urban warming.

4.2. Challenges of Rapid Afforestation in Future Greenspace Optimization and Management

With the government-led design, planning, and implementation, BPAP efficiency was generally good, if we just consider the total increased amounts of trees and connected urban forest and parks patches. Furthermore, new trees filled gaps within pre-existing greenspace patches and extended around the pre-existing green patches, which followed the original design concept, such as the aggregated-with-outlines principle for an optimal landscape [87]. However, we still need to pay attention to the unfinished afforestation in “three greenbelts” and “two green rings”, which only completed 52.4% and 20.7% of planned areas, respectively. Moreover, 24.4% of new trees were planted in locations not included in the planned area, mainly owing to the conflicts of land use, the land ownership policy and stockholder benefits [75]. Therefore, it is necessary for planners and decision makers to review and rethink their original BPAP plan scheme, and reduce unplanned adjustments of plantation sites during future rounds of plain area afforestation in Beijing.

Landscape transition detection showed that 77.5% of new forests were transferred from cropland, which means that the land replacement costs and management of replanted sites will be significant challenges. As a trading zone for food and vegetables, Beijing historically had a sufficient external food supply, which means that local traditional agriculture developed slowly with low economic benefits, and thus much cropland was dilapidated. Thus, the local government rented farmland to plant new trees during the process of BPAP, which resulted in high compensation costs for the land holders [115]. One of the initial rules for BPAP was "occupy less agricultural land as possible", however, more cropland was converted than was planned during the project implementation. In addition, as the massive use of cropland for afforestation has contravened the Red Line for Arable Land Protection for food security [116,117], the new afforestation sites located on previous farmland have high risks of being converted back to cropland when food security protection is prioritized. Thus, permanently preserving the new afforestation will be another challenge after BPAP, and a long-term monitoring system for the new replanted sites is needed.

The massive transition from cropland to forests has negative impacts on the biodiversity of agriculture as well [118]. Specifically, the loss of cropland will result in the decrease of segetal plants and traditional local crops such as alfalfa, wheat and rape [119–121]. It also threatens the ecological process of domestic animals, insectivorous birds and pollinator insects as the loss of habitats or food [122–124]. Thus, the biodiversity conservation for new afforestation is urgent needed to compensate the loss of agricultural biodiversity.

4.3. Integration of Spatial Analysis for Pre-Assessment of Afforestation Programs

There are currently two primary challenges for the assessment of new afforestation: (1) the lack of spatial distribution evaluation at a large scale after afforestation programs, with few studies focusing on landscape pattern changes before and after afforestation, and (2) the overstatement of outcomes in afforestation programs [125]. To assess the real-world outcomes of BPAP and understand the process from planning to implementation, we integrated landscape pattern, transition detection, and expansion analyses to quantify greenspace heterogeneity and spatial-temporal dynamics during the afforestation implementation [126,127]. We also visualized redundant numbers by using readability plots and diagrams to enhance the interpretation and understanding of results. Compared to those of previous afforestation program assessments, such spatial-based analysis methods can be used to measure the actual changes in quantity and spatial placement of new afforestation sites, and provide spatially explicit data to support future efforts on spatial optimization, adjustment, and ecosystem service assessment of afforestation programs [128]. For example, measuring fragmentation can help to evaluate and optimize the spatial distribution of greenspace, which is related to evenness and accessibility [127,129]; measuring landscape type transitions can monitor land use changes during the afforestation programs and identify the potential risks or challenges for future conservation and management (the potential implications of our integrated spatial analysis were listed in Table 4). However, calculation of those indicators through different tools (e.g., ArcGIS, Fragstats, and RStudio) will take significant computing time, especially for those who are not familiar with GIS or landscape analysis, suggesting that a unified platform is needed for further applications. Thus, our future work is constructing and integrating these metrics based on open-source platforms (e.g., RStudio and Python), and develop a replicable user-friendly application for the pre-assessment of afforestation.

In addition, landscape metrics and spatial analysis sometimes fail to evaluate the exact ecological functions and quantify real-world ecological processes during afforestation [130]. Thus, full afforestation assessments, specifically focusing on tree health condition, public use of the facilities, and ecosystem services such as air pollution removal, carbon storage, and heat island mitigation [131–133], are still needed based on the spatial-temporal analysis of landscape patterns.

Table 4. Potential applications of several spatial analysis.

Methods	Indicators	Potential Applications	Software
Landscape transition detection	Percentage of landscape	Measures the exact quantity, scale and direction of greenspace growth and transition to provide references for the program optimization and adjustment strategies.	ArcGIS RStudio
	Individual patch size		
Spatial pattern analysis	Mean patch size	Measures the fragmentation of greenspace to evaluate the potential impacts on urban biodiversity and ecosystem services.	Fragstats RStudio
	Area-weighted mean shape index	Measures the shape of greenspace patches to identify the potential impacts on organismal activities (e.g., migration and predation)	
Landscape expansion analysis	Landscape expansion index	Measures the process of greenspace expansion to detect the growth mechanisms of inner-city afforestation, and to evaluate whether the greenspace patterns were arranged as initially planned.	ArcGIS RStudio

5. Conclusions

Beijing initiated the largest afforestation program in its history in 2012. With a vision of two green rings, three greenbelts, nine green wedges, and multiple green corridors, more than 54 million trees were planted in four years (from 2012 to 2015) on an area of 70,711 ha. Despite the greenspace enhancement in the plain area, we lacked understanding of real outcomes regarding the changes in greenspace patterns during and after such rapid afforestation. Therefore, before a deeper assessment of ecosystem services and other costs or benefits, it was necessary to detect the spatial-temporal changes during implementation of afforestation.

Our work has confirmed that large-scale and rapid afforestation has enhanced urban greenspace by converting cropland and other land (e.g., built-up and other impervious area) into forests and urban parks. The inner-city afforestation also accelerated the conversion of very small greenspaces to larger patches, with potential positive impacts on urban resilience and conservation. After afforestation, forest patches became more aggregated despite the overall landscape fragmentation, which would benefit urban biodiversity and human well-being. However, the extra-adjustment of real afforestation sites and the massive transition between cropland and forest have been challenges for the future optimization and conservation of BPAP. The study also demonstrated that spatially explicit data and analysis can support efforts to assess rapid outcomes (e.g., both specific and cumulative changes in landscape patterns) of current ongoing afforestation programs. Based on this study, future work should focus on the full assessment of social-ecological-economic impacts for new afforestation areas and zoom in to the specific ecosystem services provided by the afforestation. In addition, more comparative research of such afforestation programs is needed for identifying the real-world efficiency of inner-city afforestation from planning to implementation.

Author Contributions: J.J. conceived the study, processed, analyzed and visualized the data, interpreted the results, and wrote the original manuscript. C.W. supervised the overall research and reviewed the draft manuscript. B.J. contributed to the spatial analysis and data curation. S.R.J.S. reviewed the manuscript and contributed to the introduction and methodology sections. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Table A1. Transition matrix of landscape patch types from 2009 to 2015 (unit: hectares).

Period	Patch Types	Other Land	Forest	Cropland	Vacant Lots	Waterbodies	Unused Land	Wetlands	Parks	Loss
2009–2013	Other land	256,207.43	2445.51					17.69	172.96	2636.15
	Forest		106,240.56					4.03	100.17	104.20
	Cropland		8906.57	201,690.33				73.08	244.91	9224.56
	Vacant lots		35.21		1773.34				11.03	46.24
	Waterbodies		101.79			6602.47		5.22	0.47	107.48
	Unused land		259.61				8703.93		0.92	260.53
	Wetlands		1525.75					29,902.07	0.45	1526.20
	Parks		332.64					0.34	34,259.52	332.98
	Gain	0	13,607.08	0	0	0	0	100.35	530.91	14,238.34
	Transition Rate	−1.02%	12.70%	−4.37%	−2.54%	−1.60%	−2.91%	−4.54%	0.57%	
2012–2013	Other land	254,223.31	1821.04					5.49	157.59	1984.12
	Forest		119,579.44					19.06	249.14	268.20
	Cropland		14,572.04	186,194.27				112.16	811.85	15,496.05
	Vacant lots		35.53		1732.80				5.02	40.55
	Waterbodies		109.22			6440.78		0.34	49.10	158.65
	Unused land		264.89				8435.89		3.15	268.04
	Wetlands		958.80					28,956.88	86.74	1045.53
	Parks		453.62					0.07	34,336.13	453.69
	Gain	0	18,215.14	0	0	0	0	137.12	1362.58	19,714.84
	Transition Rate	−0.77%	14.97%	−7.68%	−2.29%	−2.45%	−3.08%	−3.03%	2.61%	
2013–2014	Other land	252,379.94	1614.74					75.02	153.61	1843.36
	Forest		137,340.53					284.15	169.90	454.05
	Cropland		14,564.73	170,427.32				533.43	668.79	15,766.95
	Vacant lots		13.21		1718.44			1.15		14.36
	Waterbodies		156.13			6232.41		29.25	23.00	208.37
	Unused land		76.64				8359.25			76.64
	Wetlands		718.88					28,202.75	176.02	894.90

	Parks		850.50					20.05	34,828.16	870.55
	Gain	0	17,994.82	0	0	0	0	943.05	1191.31	20,129.18
	Transition Rate	−0.73%	12.73%	−8.47%	−0.83%	−3.24%	−0.91%	0.17%	0.90%	
2014–2015	Other land	251,360.78	815.04					28.46	175.66	1019.16
	Forest		155,255.65					34.22	45.47	79.70
	Cropland		3996.19	166,310.80				46.37	73.96	4116.52
	Vacant lots		4.05		1714.39					4.05
	Waterbodies		60.39			6169.81		0.09	2.12	62.60
	Unused land		16.90				8342.29		0.07	16.97
	Wetlands		213.71					28,911.95	20.14	233.84
	Parks		248.94						35,770.54	248.94
	Gain	0	5355.22	0	0	0	0	109.15	317.41	5781.78
	Transition Rate	−0.40%	3.40%	−2.42%	−0.24%	−1.00%	−0.20%	−0.43%	0.19%	

Table A2. Transition matrix of landscape patch-size classes from 2009 to 2015 (unit: percent). The numbers in the table represented the changed proportion of land area for each patch-size class and corresponded to the width of flow lines between stacked vertical bars in Sankey diagram in Figure 5.

Period	Patch-Size Classes	Very Small	Small	Medium	Large	Very Large	Huge	Loss
2009–2012	Very small	18.90	0.30	0.14	0.14	0.12	0.19	0.89
	Small	0.15	15.20	0.37	0.27	0.19	0.21	1.19
	Medium	0.03	0.12	8.26	0.34	0.13	0.23	0.85
	Large	0.02	0.06	0.11	10.30	0.57	0.20	0.95
	Very large	0.02	0.07	0.06	0.05	8.80	0.96	1.16
	Huge	0.12	0.11	0.00	0.17	0.14	32.96	0.55
	Gain	0.35	0.65	0.68	0.98	1.14	1.79	5.59
2012–2013	Very small	17.99	0.45	0.13	0.12	0.16	0.22	1.08
	Small	0.14	14.16	0.65	0.48	0.27	0.30	1.85
	Medium	0.05	0.19	7.73	0.52	0.27	0.30	1.34
	Large	0.02	0.08	0.01	10.12	0.69	0.51	1.31
	Very large	0.01	0.00	0.00	0.01	9.00	1.01	1.02
	Huge	0.04	0.04	0.06	0.09	0.16	34.02	0.39
	Gain	0.27	0.77	0.85	1.21	1.55	2.34	6.98
2013–2014	Very small	16.52	0.54	0.18	0.25	0.14	0.26	1.37
	Small	0.26	12.99	0.76	0.57	0.27	0.35	2.21
	Medium	0.02	0.14	7.38	0.71	0.28	0.17	1.32
	Large	0.05	0.06	0.08	9.76	1.12	0.58	1.89
	Very large	0.04	0.03	0.03	0.10	8.70	1.87	2.07
	Huge	0.07	0.06	0.06	0.14	0.12	35.34	0.45
	Gain	0.44	0.84	1.10	1.77	1.93	3.23	9.31
2014–2015	Very small	16.26	0.17	0.04	0.10	0.06	0.06	0.42
	Small	0.03	13.51	0.19	0.13	0.16	0.07	0.58
	Medium	0.001	0.03	8.02	0.41	0.12	0.02	0.58
	Large	0.01	0.02		11.31	0.53	0.12	0.68
	Very large	0.01	0.02		0.07	10.12	0.47	0.57
	Huge	0.01	0.04	0.00	0.03	0.07	37.79	0.16
	Gain	0.06	0.28	0.23	0.75	0.94	0.73	2.98

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