Landscape Architecture

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Annual Conversion of Green-Space Expansion into Socioeconomic and Ecological Benefit in Xi'an, China

Patrick Lewis[*]

School of Environmental Planning and Design Continental Research University France

[*] Correspondence: patrick_lewis@gmail.com

Abstract

Green space statistics in the annual unit may overestimate the effectiveness of planning efforts if the two are not correlated in their movement. This study applies the ERC analysis to Xi'an, China, based on the 2009–2019 series of annual statistics on per capita green space area, built-up land, socioeconomic benefit, ecological benefit, overall benefit, and four ecological processes, namely cooling, humidification, oxygen release, and carbon fixation. Each increase/decrease in green space area is matched with changes in socioeconomic and ecological performance, in a way that the annual information is transformed to ten successive intervals. Based on this transformation, this analysis computes conversion yield, productive conversion, expansion lag, contraction stress, recovery without expansion, and ecological coordination as the minimum of four ecological process scores. Xi'an had five productive conversion intervals, three expansion lag intervals, one contraction stress interval, and one recovery interval without any scale increase. The best interval was 2016–2017: the increment in per capita green space area was 1.70 m^2 $person^{-1}$, and that of socioeconomic, ecological, and overall benefit was 0.21, 0.18, and 0.20, respectively, leading to a highest conversion yield of 0.118 score units for each m^2 $person^{-1}$ of new green space area. The intervals of 2011–2012, 2012–2013, and 2015–2016 indicated that additional green space area does not correlate well with benefit response. In particular, ecological coordination was best in 2017, in which four ecological process scores were at or above 0.69, while the 2015 combination of good ecological score and low humidification floor (0.03) revealed ecological imbalance. It appears that annual green space performance in Xi'an relied heavily on conversion yield and ecological process balance rather than on per capita green space area. The target of 28.5–29.0 m^2 $person^{-1}$ can be justifiable if coupled with monitoring of conversion yield and minimum ecological process score.

Keywords: urban green space; annual transition analysis; ecological coordination; benefit conversion; Park City; Xi'an; ecological process floor

1. Introduction

Today, green space is required to play public service infrastructure, ecological regulatory role, environment conducive to health, and climate adaptation role. This wide-ranging functionality of green spaces has made their planning go beyond simple land reservation or beautification of public facilities. From greenways, lawns, shrubs, forests to street tree planting projects, green spaces impact on outdoor air temperatures, air moisture, landscape

Received: 08 June 2023; Revised: 20 August 2023; Accepted: 20 November 2023; Published: 30 December 2023.

doi: 10.70517/la20231134-09

character, property value, recreation, public health, and environmental justice [3, 8, 18, 30, 34]. The challenge here is the difference in maturation periods for various green space functions. While newly developed green spaces could increase per capita green-space land area right away, their effects in cooling, evapotranspiration, carbon fixation, oxygen release, utilisation, and surrounding socioeconomic development might take several years to form.

This timing feature becomes important during rapid urban growth. Since the late twentieth century, China has experienced considerable changes in population distribution, land development, demands on urban infrastructure, and environmental exposure [6, 21, 37, 39]. Urban expansion brings greater access to jobs and public service facilities but simultaneously creates more impervious surfaces, heat island problems, and needs for environmental amenity [11, 27, 40]. Against such background, the Park City paradigm was formed as an attempt to balance ecological considerations, public welfare, and urban development quality [12, 26, 38, 46]. However, for practical urban planning, the Park City idea means more than high per capita green-space area. It requires proof of successful conversion of the land-provision policy to actual ecological or socioeconomic performance.

Many studies have explained the importance of green-space supply. Green spaces could lower surface air temperature due to shadowing, evapotranspiration, increased surface roughness, and energy radiance absorption [1, 2, 4, 9, 15, 29]. Vegetated surfaces and urban trees reduce heat exposure in hot climates, whereas their efficacy depends on canopy formation, spatial coverage, and interaction with impervious surfaces [47]. Moreover, the ecological roles of green space are not limited to temperature regulation and include water regulation, cultural service, recreation, biodiversity protection, and public appreciation of the environment [8, 41, 42, 45]. On the other hand, carbon fixation, oxygen release, and other biogeochemical processes rely on vegetation species composition, biomass, growth conditions, maintenance practice, and soil activity [10, 14, 22, 23, 25]. In other words, the same green-space land area could be associated with completely different levels of ecological performance depending on maturity and planting pattern.

Socioeconomic benefits of green spaces follow a different dynamic pathway. Investment in green spaces could attract tourists, contribute to positive image, stimulate job creation, develop public service, and enhance property value but this process largely depends on institutional initiative, accessibility to green areas, market reaction, and surrounding development context [7, 17, 31]. Therefore, a city can continue to demonstrate good socioeconomic scores even when its ecological scores decline, and vice versa. Consequently, combining socioeconomic and ecological indicators and interpreting them as interchangeable can lead to misrepresentation of the true level of green-space performance.

Several literatures also show that high-density development imposes competition on the spatial allocation and function provision of green spaces. Densification tends to create fragmented green spaces, reduce open spaces, and make the design of parks and corridors more challenging [13, 32, 36]. Accessibility research has improved our understanding about who could access and utilise green spaces and how park distribution influences public visitation [5, 16, 28]. Meanwhile, ecosystem service research helps us to understand the benefits that different green-space categories bring about. Nevertheless, the urban planner still faces the following critical question. When the per-capita scale of green spaces is annually growing, does it mean that the city successfully turned it into actual benefit or simply added new green spaces that were unable to exert a comprehensive effect?

This paper takes Xi'an 2009–2019 record as a series of transitions in order to see how annual scale changes affected comprehensive green-space benefit conversion and which ecological processes limited green-space performance. Contrary to quota selection, curve fitting, and annual threshold ranking, this analysis identifies the intervals that generated benefit, the periods during which growing green spaces failed to improve ecological or overall performance, and the ecological processes that imposed constraints on the annual benefit generation. The objective of this exercise is to help urban planners distinguish productive scale change and scale lagging or imbalance.

2. Theoretical context and evidence base

2.1. Green-space scale and performance divergence

It is advantageous to examine per-capita green space as the simplest indicator reflecting the relationship between green-space land provision and demand by the population. However, the problem with a scale-based evaluation lies in the possibility that urban expansion could hinder ecological performance or socioeconomic development even if the scale remained satisfactory. In addition, a city with high green-space land area might demonstrate unevenness in terms of green-space accessibility or quality. This is the reason why the scale is only partially informative in measuring green-space performance.

As part of the optimal-scale research, some studies have proved that city systems can operate outside the range of scales within which they achieve reasonable balance between benefits and costs [19, 33, 35, 44]. Concerning the specific subject matter, Pang et al. [24] estimated the socioeconomic, ecological, and comprehensive thresholds of green-space benefit in Xi'an and argued that per-capita green-space area had to be higher than 24.89 m^2 $person^{-1}$ to ensure benefit sustainability. This information is quite helpful but incomplete in the sense that the city could exceed the threshold level without adequate ecological or socioeconomic performance.

The transition approach helps us to fill this gap. Instead of focusing on whether a certain year exceeds the optimal scale, we need to examine how the urban system evolves between two consecutive years. This approach is useful when we deal with the planning of green-space construction, planting, maintenance, public facility provision, and surrounding development activities. Any increase in green-space scale can be considered meaningful only when it leads to improvement in socioeconomic and ecological performance. Otherwise, annual growth in green-space scale is irrelevant to practical urban planning despite the fact that it exceeds the target value.

2.2. Ecological performance of urban vegetation

From an ecological viewpoint, green space benefits are highly complex. Cooling ability of green space relies on shading, evapotranspiration, vegetation coverage, aerodynamic interaction, impervious surfaces, and meteorological conditions [2, 9, 15]. Similarly, humidification is determined by plant transpiration and soil water content [20, 43]. Carbon fixation and oxygen release are controlled by vegetation photosynthesis and growth conditions [10, 14, 23]. The differences among those indicators mean that ecological performance could vary significantly depending on the particular meteorological situation, surrounding landscapes, and vegetation management.

This complexity becomes especially important in a continental and semi-arid environment where moisture, heat, and vegetation survival tend to interact intensively. If cooling is significant but humidification is insignificant, people still face discomfort when they step out. If the city performs poorly in cooling but has high scores for carbon, oxygen and other aspects, there could be a gap between ecological productivity and the comfort of people. In case of insignificant cooling and oxygen release, high humidification might indicate temporary improvement caused by current moisture rather than sustainable vegetation structure. Therefore, in addition to high ecological scores, the planning tool must consider the least performing component and determine whether any ecological function is underdeveloped.

To accomplish this purpose, the functional floor concept used in this study is appropriate. Functional floor means the lowest score for cooling, humidification, oxygen release, and carbon fixation within a given year. High floor implies that all four components perform satisfactorily, whereas low floor implies that there are components with poor performances despite the overall acceptable ecological scores. Besides the functional floor, component spread will be included into calculation to measure how diverse and uneven ecological performance was during the year. By using these two measures, planners could learn about ecological performance without making assumptions about compensating effects of all components.

2.3. Rapid urbanisation and comprehensive benefit realisation

Urban expansion makes green-space benefit performance even more sensitive. The more urban development occurs, the larger the territory green space has to regulate and serve. Thus, per-capita green space is expected to show different results in different years despite the similar land area. What would be an appropriate green-space scale under low urbanisation could be inadequate when the surrounding environment grows rapidly. In this context, benefit conversion becomes more informative than benefit score alone.

By definition, conversion measures how many units of combined benefit change for each unit of increased per-capita green-space area. A positive conversion result means that the increased scale of green space is successfully transformed to higher benefit performance. On the contrary, a negative conversion result shows the failure of green-space scale increase to bring about positive benefit outcomes. This does not necessarily mean inefficiency in green-space construction but reflects issues related to ecological lag, rapid urban expansion, delayed vegetation maturity, or spatial mismatch between new green spaces and green-space demand locations. The advantage of this analytical perspective is to pinpoint the exact stage of development where something went wrong.

The benefit-conversion method also enhances the meaning of high benefit scores. Although such a score represents impressive performance, it might lose its significance if one type of benefit outweighs others or the previous benefit score is low. For this reason, benefit transition classification includes not only expansion with beneficial effect and expansion lag but also contraction with deteriorated performance and recovery without additional expansion.

3. Study area and analytical data

3.1. Xi’an urban development record, 2009–2019

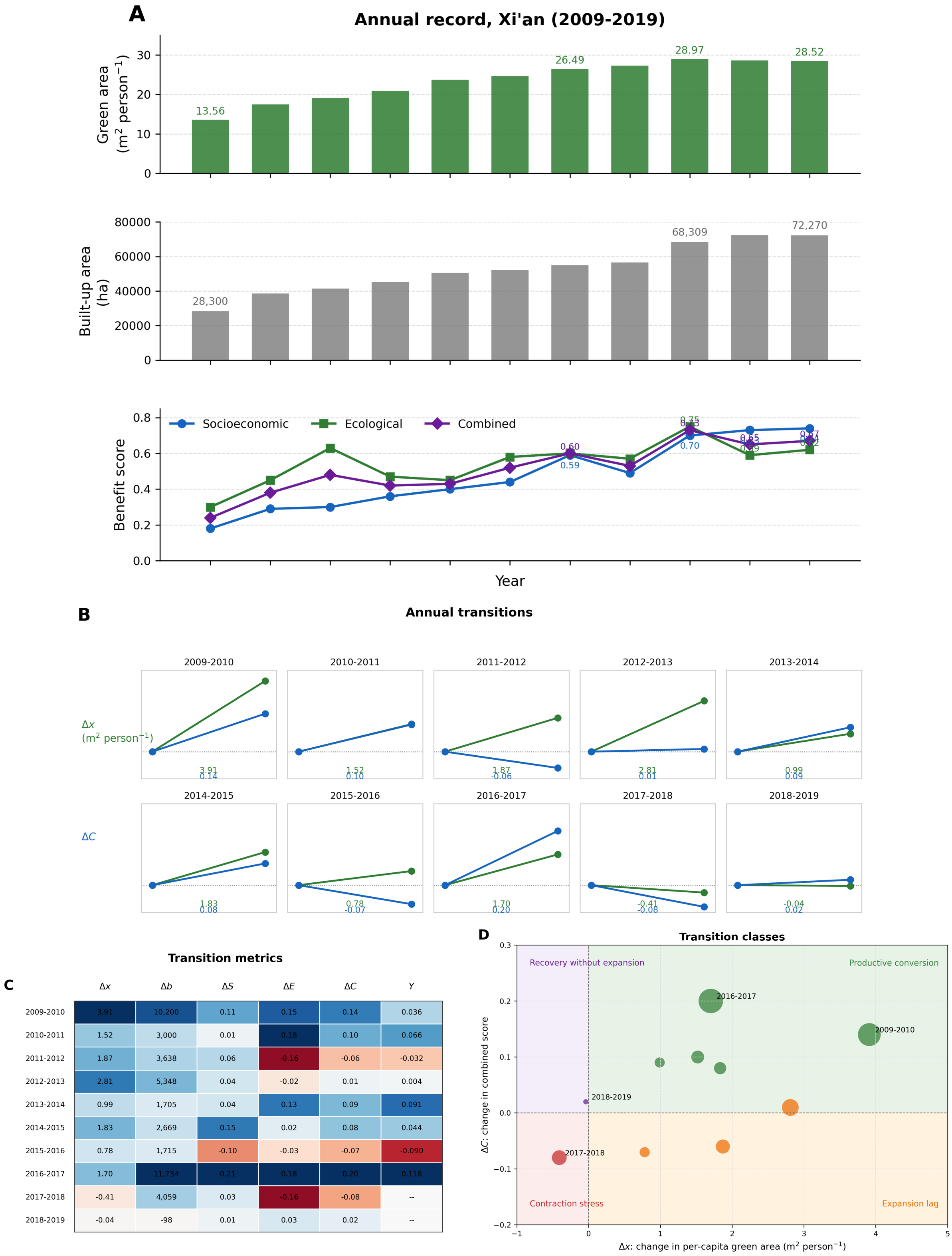
The Xi’an municipal district located in northwest China is a convenient example of rapid urban expansion during 2009–2019. The city is interesting in terms of green-space planning analysis because its record during this period included changes in population, built-up area, per-capita green-space area, microclimate, socioeconomic and ecological benefits. The analytical work draws upon Xi’an 2009–2019 table published by Pang et al. [24]. The dataset includes socioeconomic indicators, ecological functions indicators, permanent population, built-up area, per-capita green-space area, cooling intensity, humidification, socioeconomic score, ecological score, combined score, and cooling, humidification, oxygen release, and carbon-fixation indicators.

Rather than analysing the annual record directly as a set of states and their associated scores, we need to transform annual values into transitions. The first dataset will contain annual state data including the following variables – per-capita green-space area, built-up area, cooling intensity, humidification, socioeconomic score, ecological score, combined score, and scores for four ecological components. In contrast, the second dataset will include transitions for 2009–2010 to 2018–2019 with the following data on each transition – increase in green-space area, increase in built-up area, increase in benefit scores, functional floor, and ecological component spread.

The four ERC panels in Figure 1 show how the analysis moves from the annual Xi’an record to interval-level interpretation. The first panel preserves the annual states; the second converts adjacent years into transition units; the third lists the calculated increments; and the fourth assigns each interval to a performance class. This visual sequence is important because the paper’s results depend on whether land addition, socioeconomic gain, ecological gain, and combined-score change occur together.

The annual values in Table 1 show the core empirical tension. Per-capita green area more than doubled, built-up area expanded by more than two and a half times, and the combined score increased from 0.24 to 0.67. The same record also shows instability: the ecological score fell from 0.63 in 2011 to 0.47 in 2012 despite a higher per-capita green area, and the combined score declined from 0.60 in 2015 to 0.53 in 2016 while green-space scale continued to rise. These movements justify a transition analysis because annual levels alone cannot explain whether added green area was being converted into benefit.

The annual panorama in Figure 2 places the land supply, built-up expansion, and benefit scores in the same chronological order. The first panel of the annual transition shows a rapid growth in per-capita green area, accompanied by an even faster absolute growth in built-up area. The second panel reveals that the ecological benefit was not a direct prolongation of the land supply pattern, since ecological benefit peaked in 2017, declined in 2018, and showed partial recovery in 2019. The final panel makes clear that 2015, 2017, 2018, and 2019 are distinct planning periods, all falling within the high range of green-space supply.



	Δx	Δb	ΔS	ΔE	ΔC	Y
2009-2010	3.91	10,200	0.11	0.15	0.14	0.036
2010-2011	1.52	3,000	0.01	0.18	0.10	0.066
2011-2012	1.87	3,638	0.06	-0.16	-0.06	-0.032
2012-2013	2.81	5,348	0.04	-0.02	0.01	0.004
2013-2014	0.99	1,705	0.04	0.13	0.09	0.091
2014-2015	1.83	2,669	0.15	0.02	0.08	0.044
2015-2016	0.78	1,715	-0.10	-0.03	-0.07	-0.090
2016-2017	1.70	11,734	0.21	0.18	0.20	0.118
2017-2018	-0.41	4,059	0.03	-0.16	-0.08	--
2018-2019	-0.04	-98	0.01	0.03	0.02	--

Figure 1. ERC annual record.

Table 1. Annual state variables.

Year	x (m^2 person^{-1})	Built-up (ha)	Cooling (°C)	Humid. (%RH)	S	E	C	Floor
2009	13.56	28,300	3.66	13.09	0.18	0.30	0.24	0.16
2010	17.47	38,500	3.58	23.99	0.29	0.45	0.38	0.08
2011	18.99	41,500	4.49	21.95	0.30	0.63	0.48	0.26
2012	20.86	45,138	4.42	19.86	0.36	0.47	0.42	0.23
2013	23.67	50,486	3.34	18.93	0.40	0.45	0.43	0.04
2014	24.66	52,191	5.24	17.83	0.44	0.58	0.52	0.51
2015	26.49	54,860	4.66	10.49	0.59	0.60	0.60	0.03
2016	27.27	56,575	4.78	14.50	0.49	0.57	0.53	0.29
2017	28.97	68,309	7.08	20.44	0.70	0.75	0.73	0.69
2018	28.56	72,368	4.78	22.19	0.73	0.59	0.65	0.32
2019	28.52	72,270	4.50	14.43	0.74	0.62	0.67	0.24

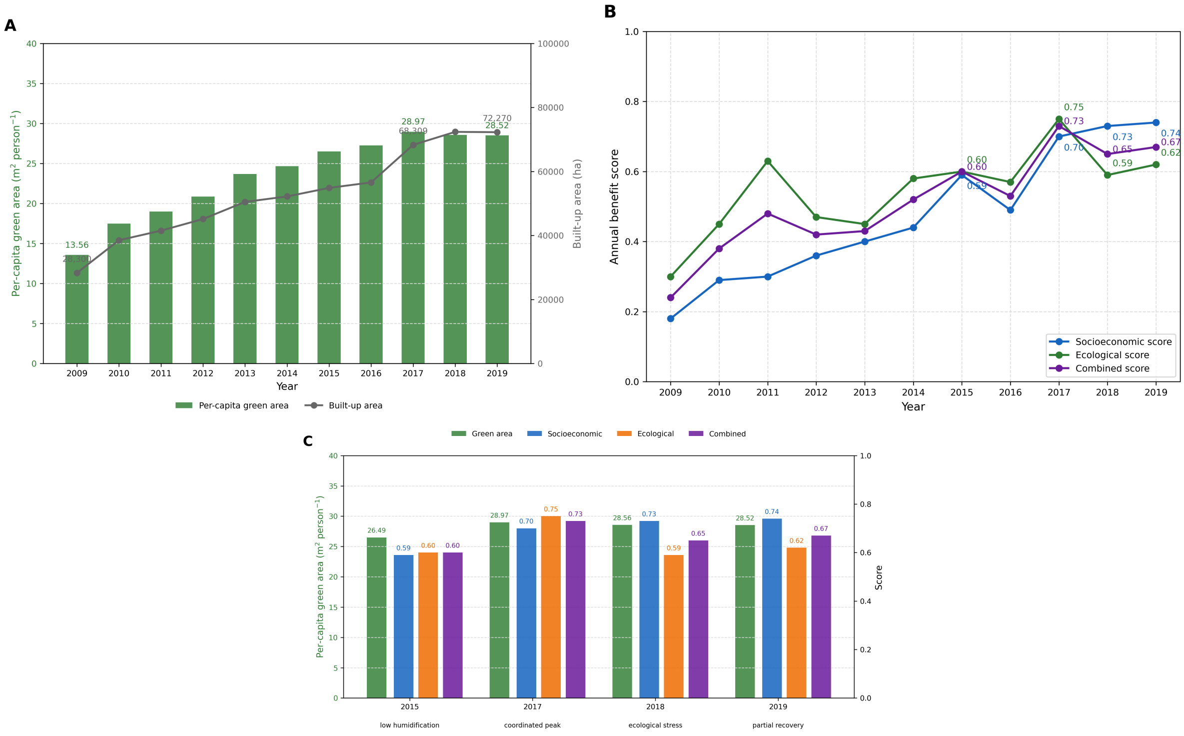


Figure 2. Green-space scale and built-up land.

3.2. Ecological process indicators

Let D_t, H_t, O_t, and F_t be the annual scores for cooling, humidification, oxygen release, and carbon fixation, respectively. The ecological functional floor is defined as

$$\phi_t = \min(D_t, H_t, O_t, F_t), \tag{1}$$

while the component spread is defined as

$$\psi_t = \max(D_t, H_t, O_t, F_t) - \min(D_t, H_t, O_t, F_t). \tag{2}$$

Neither term intends to replace the ecological score. Both intend to show whether all ecological processes are responsible for the score or just a subset of them. A high floor and a low spread show coordinated ecological

doi: 10.70517/la20231134-09

functioning, while a low floor and a high spread imply one component as the limiting factor in ecological functioning, regardless of an apparently acceptable ecological score.

Such interpretation matters to the ecological profile of Xi'an, since the ecological components peak at different times. Cooling peaks in 2017, humidification in 2010, and oxygen release and carbon fixation in 2015. An ecological score would average these differences, but the floor and spread would uncover the underlying discrepancy. Thus, it becomes possible to distinguish between a generally good year and a perfectly balanced ecological year.

4. Expansion–response conversion analysis

4.1. Annual transition indicators

For each interval between $t-1$ and t, the difference in per-capita green area is denoted as

$$\Delta x_t = x_t - x_{t-1}, \tag{3}$$

while analogously ΔS_t, ΔE_t, ΔC_t, ΔB_t, $\Delta\phi_t$, and $\Delta\psi_t$ are the changes in the socioeconomic score, the ecological score, the combined score, built-up area, the ecological floor, and the ecological component spread, respectively. The expansion transition dataset is thus based on ΔS_t, ΔE_t, ΔC_t, ΔB_t, $\Delta\phi_t$, and $\Delta\psi_t$, where B_t is built-up area.

The yield ratio for expansion intervals is

$$\eta_t = \frac{\Delta C_t}{\Delta x_t}, \quad \Delta x_t > 0.5. \tag{4}$$

The minimum 0.5 mpp filter serves to exclude cases of very small or negative scale changes from the calculation of land-addition efficiency. The lack of land addition (or contraction stress) is interpreted separately from other types of annual transitions. This is necessary because a positive ΔC_t following a negative Δx_t cannot indicate efficiency of new land; it indicates effective use, delayed maturation, measurement response, or improved external condition.

The domain substitution ratio is

$$\sigma_t = \Delta S_t - \Delta E_t, \tag{5}$$

positive for an excess of socioeconomic benefit over ecological benefit, and negative for the opposite situation. The domain substitution ratio is useful when the combined score increases but its two domains remain asynchronous.

4.2. Classification of annual performance transitions

Each interval is placed into one of four classes of transition. A productive conversion interval corresponds to a rise in per-capita green area exceeding 0.5 m^2 person^{-1}, as well as simultaneous growth in the combined score, socioeconomic score, and ecological score. In contrast, an expansion lag corresponds to a rise in per-capita green area above 0.5 m^2 person^{-1}, along with a failure of the combined score, socioeconomic score, or ecological score to grow. Contraction stress corresponds to no green-space expansion, alongside the decline in the combined score. Finally, recovery without expansion is defined as a rising combined score with negligible or negative change in green space.

These classes are intentionally conservative. They assume no specific causality behind a negative transition; factors other than green-space planning may be responsible, such as weather, urban development, vegetation age, investment, and measurement procedures. Instead, their objective is interpretative: to indicate intervals where the planner should seek explanations for added benefit, lack thereof, or benefit improvement without land increase.

With the introduction of the transition calculations in Table 2, the record for Xi'an takes on a new interpretation. First, the largest land-gain interval (2009–2010) does not have the highest conversion efficiency, only an average 0.036. The highest conversion efficiency belongs to 2016–2017, during which the combined score gained by 0.20 in response to the gain of 1.70 in per-capita green area. Second, the three intervals that gained positive land do not show clear functional conversion: 2011–2012, 2012–2013, and 2015–2016. This result is critical because it demonstrates that land expansion alone cannot serve as an indicator of green-space function.

Table 2. Annual transition calculations.

Interval	Δx	ΔS	ΔE	ΔC	η	Class
2009–2010	3.91	0.11	0.15	0.14	0.036	Productive conversion
2010–2011	1.52	0.01	0.18	0.10	0.066	Productive conversion
2011–2012	1.87	0.06	-0.16	-0.06	-0.032	Expansion lag
2012–2013	2.81	0.04	-0.02	0.01	0.004	Expansion lag
2013–2014	0.99	0.04	0.13	0.09	0.091	Productive conversion
2014–2015	1.83	0.15	0.02	0.08	0.044	Productive conversion
2015–2016	0.78	-0.10	-0.03	-0.07	-0.090	Expansion lag
2016–2017	1.70	0.21	0.18	0.20	0.118	Productive conversion
2017–2018	-0.41	0.03	-0.16	-0.08	–	Contraction stress
2018–2019	-0.04	0.01	0.03	0.02	–	Recovery without expansion

5. Results

5.1. Urban expansion and benefit response

Xi'an has gone through three main stages since 2009 until 2019. During the first stage (2009 to 2011), there was significant improvement in per-capita green space and the combined benefit. The former expanded from 13.56 to 18.99 m^2 person^{-1}, and the latter went up from 0.24 to 0.48. In particular, there was greater improvement in the ecological domain than in the socioeconomic domain, especially from 2010 to 2011. The result suggests that initial gains resulted from ecological reaction, albeit on the background of low-scale humidification.

The second stage is from 2011 to 2016, which was characterized by instability. The per-capita green area was expanding, from 18.99 m^2 person^{-1} to 27.27 m^2 person^{-1}, yet the combined score varied greatly to finally stay at 0.53. The ecological score decreased drastically from 2011 to 2012, was only moderate in 2012 to 2013, recovered somewhat in 2013 to 2014, but fell back from 2015 to 2016. Meanwhile, the built-up area grew from 41,500 ha to 56,575 ha. The information shows that this stage was not just one of increasing green-space scale but also a stage of delayed or uneven functional manifestation.

As for the third stage (2016 to 2019), the transition from 2016 to 2017 is the most prominent feature. Notably, the benefit gained from that transition is larger than any other transition, and both the socioeconomic and ecological scores increased. The subsequent transition from 2017 to 2018 reduced some of the gains. Specifically, the per-capita green area dropped slightly, and the ecological score dropped from 0.75 to 0.59. Although the socioeconomic score gained slightly from 0.70 to 0.73, the combined score declined significantly to reach 0.65. Lastly, there is recovery without added land in the final 2018–2019 transition.

In terms of the transition typology in Figure 3, productive transitions occur when green-space scale changes positively and so does benefit. On the contrary, expansion-lag transitions indicate that adding per-capita green area does not lead to proportional increase in comprehensive benefit. Apart from noticing that 2016–2017 produced the largest benefit gain, it is noteworthy that it showed high conversion with concurrent sharp built-up area growth. In this sense, there can still be successful conversion of benefits even with great urban pressure.

5.2. Expansion lag and conversion yield

The conversion yields show the varying benefits that Xi'an achieved from its green-space addition. The highest among them is 0.118 combined score units per m^2 person^{-1} in the 2016–2017 transition. The second-highest is 0.091 from the 2013–2014 transition, despite its small 0.99 m^2 person^{-1} land expansion. Next are 0.066 from 2010–2011 and 0.044 from 2014–2015. Lastly, the 2009–2010 transition has the largest gain of 2.43 m^2 person^{-1}, yet the lowest yield of 0.036, which indicates that land increase does not mean high benefit conversion efficiency.

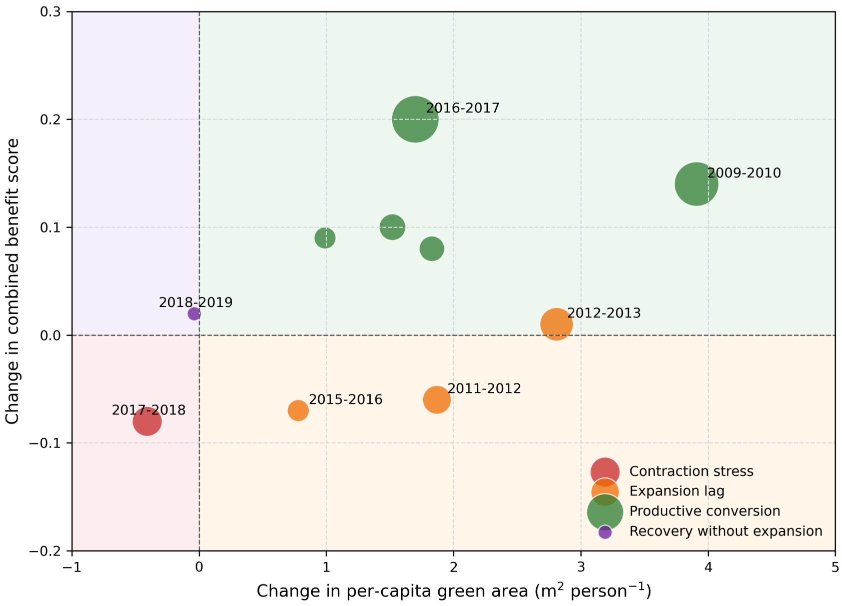


Figure 3. Transition typology.

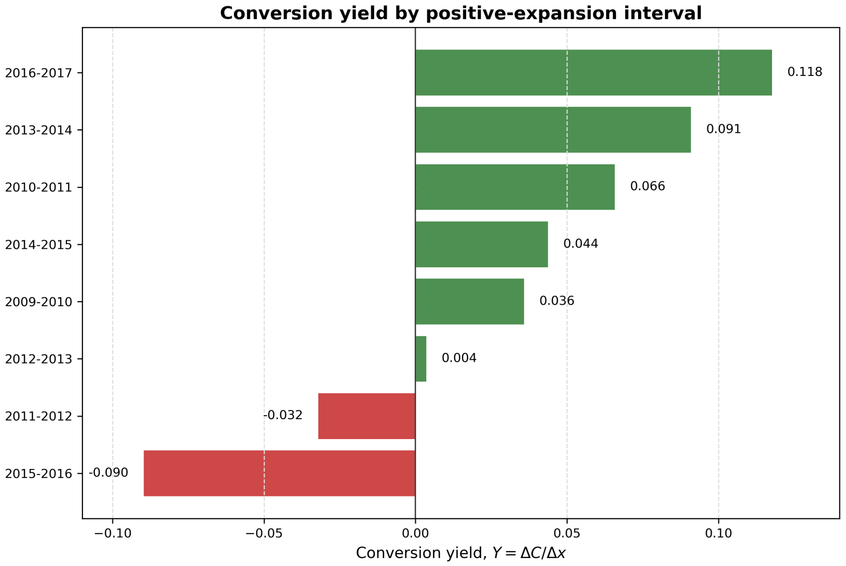


Figure 4. Conversion yield.

From the sorted yield plot in Figure 4, it is clear that the reason why 2016–2017 shows the best conversion is not simply due to the fact that it occurred after the highest land-supply level. The real reason is that it produces 0.118 combined score units per added m^2 person^{-1}, the largest yield of the series. In comparison, the yield in 2012–2013 is extremely low, despite its substantial land increase of 2.81 m^2 person^{-1}. Meanwhile, 2011–2012 and 2015–2016 yielded negatively. It is apparent that added green area and effective benefit conversion are different indicators.

Specifically, the expansion-lag years were 2011–2012, 2012–2013, and 2015–2016. In the 2011–2012 interval, per-capita green area grew by 1.87 m^2 person^{-1} but caused a decline in the combined score (-0.06). Moreover, the ecological score dropped from 0.54 to 0.38, leading to the lowest gain in ecological benefit. In 2012–2013, although the per-capita green area grew by 2.81 m^2 person^{-1}, there was no notable change in benefit except a marginal gain of 0.01 combined score units. Also, the 2015–2016 interval shows negative yields because all scores fell despite green area increment. Thus, the three intervals indicate that Xi'an's green spaces experienced phases of poor benefit output.

Nevertheless, it would be inaccurate to conclude that green-space expansion did not make contributions to improving ecological benefit. The more accurate interpretation of those years is that the newly-added land did not immediately surpass urban, ecological, or atmospheric pressures. The reasons can include insufficient vegetation establishment, inappropriate land location, inadequate maintenance, high environmental variability, nearby impervious surface, etc. As for planning analysis, the information is valuable as it helps identify the intervals that need more attention to find the exact reasons.

5.3. Domain-specific annual changes

Understanding the domain increments sheds light on the changes that might not fit the expected trends. In particular, the 2010–2011 interval is characterized by dominance of ecological benefits. The benefit increment in the domain is 0.18 compared to 0.01 in the socioeconomic domain. However, the 2014–2015 interval exhibits the opposite trend as the socioeconomic benefit increased by 0.15 but the ecological benefit only rose by 0.02. Finally, the substitution occurs clearly during the 2017–2018 interval because the benefit increment of the socioeconomic domain is 0.03 while that of the ecological domain is -0.16.

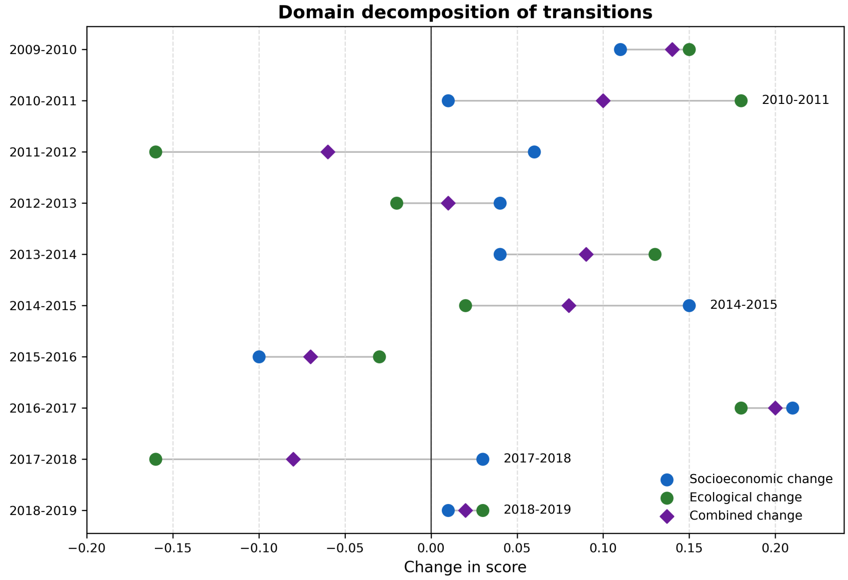


Figure 5. Domain decomposition.

From the domain decomposition in Figure 5, it is observed that the two domains do not always vary consistently. There are several years when either the socioeconomic or ecological domain dominates, especially 2017–2018. The interval shows increasing the socioeconomic score by 0.03 while reducing the ecological score drastically. In other words, the comprehensive score might mask the ecological degradation. Therefore, it can be helpful to analyze the two domains separately for proper planning analysis.

Finally, the 2018–2019 transition is notable for another reason. In this transition, there is little change in the per-capita green area, yet the ecological and combined scores both exhibit modest improvement. This indicates that there can be functional adjustment, delayed ecological response, appropriate management, or favorable environmental conditions that contribute to higher scores. The value for the planning approach here is that, when it is hard to expand lands, improvement in benefit may depend on other factors.

5.4. Ecological process floor and component spread

The results about functional floors bring up another dimension to evaluate the green-space function. Specifically, the ecological score of 2015 is 0.60, close to that in 2019. Nevertheless, the functional floor is only 0.03 due to weak humidification performance. Furthermore, the component spread is very high, 0.87. As a result, despite having acceptable ecological score, Xi'an's green spaces failed to coordinate the performance of their components in 2015. Oxygen release and carbon fixation are both 0.69, but humidification is much lower at 0.03.

In 2017, Xi'an reaches a much higher score of 0.75, and its functional floor is also fairly high (0.69). Specifically, cooling, humidification, oxygen release, and carbon fixation all show excellent performance with their score at 1.00 or 0.69. The difference is in the component spread, which is reduced to 0.31 in 2017 from 0.87 in 2015. As a result, it can be claimed that the reason for reaching 0.75 in ecological benefit in 2017 is the coordination of all ecological components.

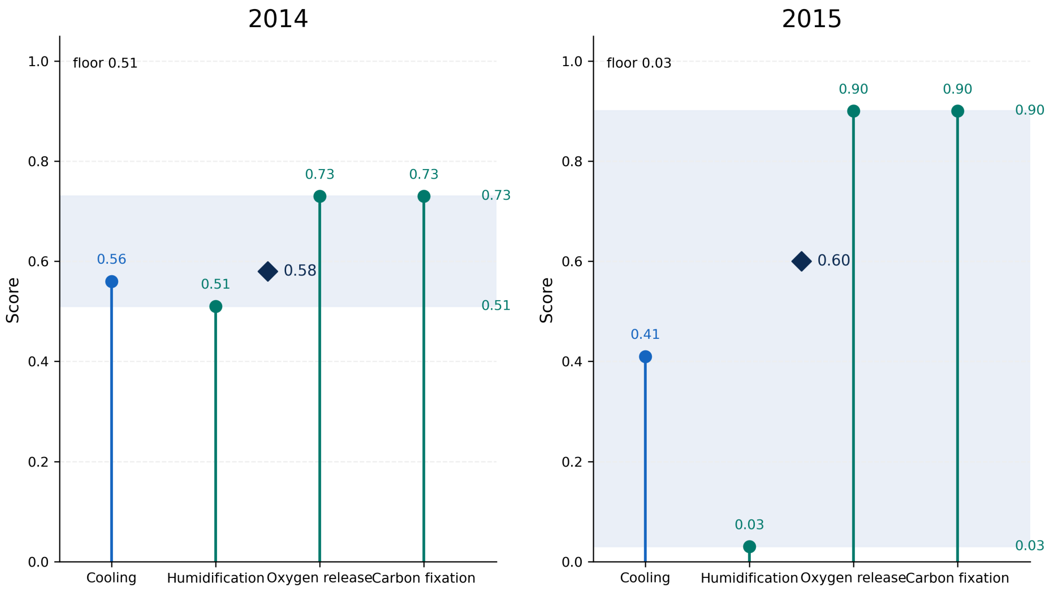


Figure 6. Ecological components, 2014–2015.

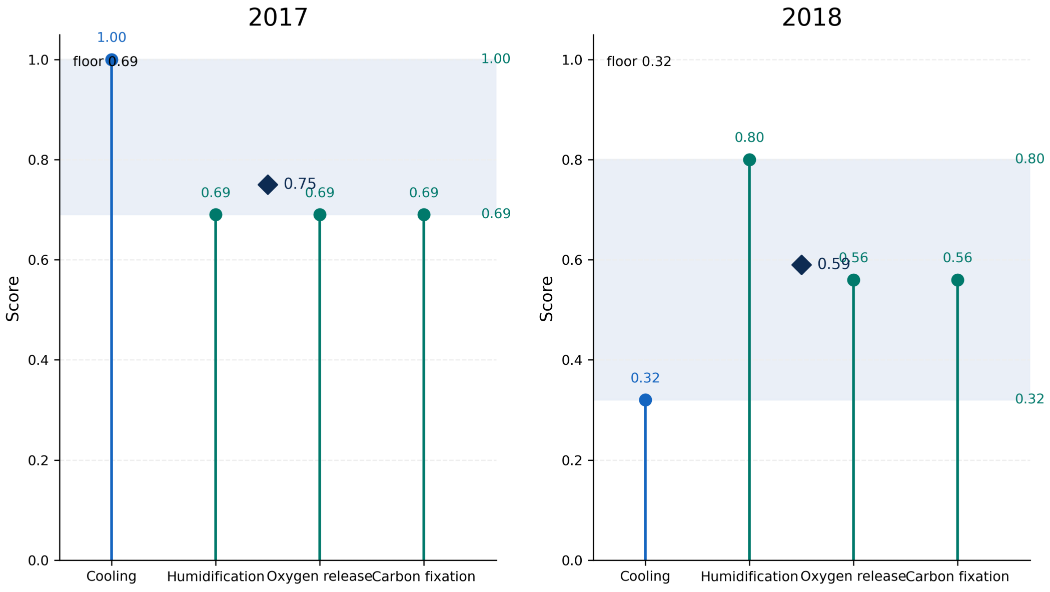


Figure 6. Ecological components, 2017–2018.

The ecological process portraits in Figure 6 show the ecological bottleneck clearly. While composite ecological scores are valuable, the functional floor makes clear the ecological process that constrains the ecosystem. This constraint in 2015 becomes especially important as it prevents this year from being classified as a state that is completely coordinated. On the other hand, the functional floor in 2017 reveals the only state that combines all three ecological processes in their strong state.

The data of 2018 and 2019 years demonstrate several types of recovery. For example, in 2018, the functional floor was 0.32 and humidification was high at 0.80, while cooling became weak at 0.32 and biogeochemical functions were scored 0.56. In 2019, improvement occurred in terms of oxygen release and carbon fixation, which reached

0.85 each. However, the functional floor was 0.24 because cooling was poor (0.20) and humidification dropped to 0.29. As one can see, in Xi'an, the problem of ecology after 2017 does not lie in the decline. It is a shift of the bottleneck between various ecological processes.

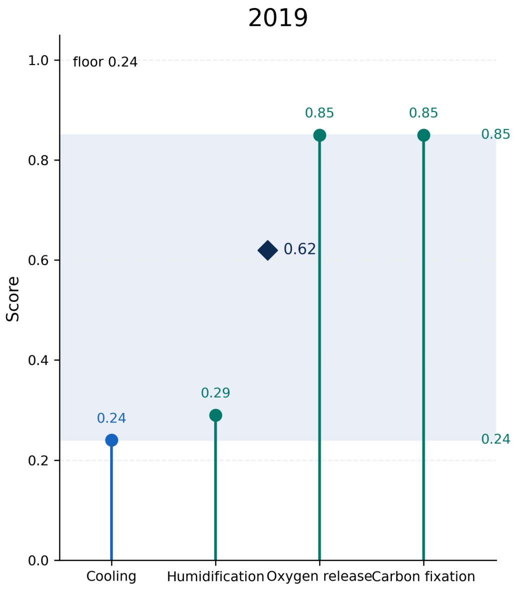


Figure 6. Ecological components, 2019.

Table 3. Ecological coordination.

Year	Cooling	Humid.	Oxygen	Carbon	Floor	Spread
2010	0.08	0.91	0.36	0.36	0.08	0.83
2011	0.26	0.79	0.62	0.62	0.26	0.53
2014	0.56	0.51	0.73	0.73	0.51	0.22
2015	0.41	0.03	0.90	0.90	0.03	0.87
2017	1.00	0.69	0.69	0.69	0.69	0.31
2018	0.32	0.80	0.56	0.56	0.32	0.48
2019	0.24	0.29	0.85	0.85	0.24	0.61

These specific records illustrate the importance of considering functions when interpreting ecological score. Even if 2014 recorded a weaker ecological score than 2015, the former also had a very strong floor and very narrow component spread, showing that components were much better balanced in that year. 2015 recorded good biogeochemical performance but showed very poor humidification performance. The record in 2017, however, displayed the best cooling performance with also a very strong minimum across the remaining functions.

5.5. Combined transition contrast

The integrated analysis contrasts scale change, built-up pressure change, domain increments, combined-score response, and ecological-floor movement. It helps distinguish intervals caused by land expansion, those caused by benefit response, or ecological coordination. For example, the 2016–2017 transition showed significant increases in per-capita green area, built-up area, socio-economic benefit, ecological benefit, combined benefit, and functional floor. The 2011–2012 transition was opposite, as it showed increases in per-capita green area and socio-economic score but declines in ecological score and combined score. The 2017–2018 transition demonstrated contraction stress as it displayed declines in both green-space scale and ecological performance but still had an expanding built-up area.

From this reading, we see that transition analysis reveals differences between intervals from the perspective of green-space conversion. Built-up growth was not automatically undesirable in an interval like 2016–2017, but when ecological performance failed to respond positively, it became a problem. Functionally speaking, we note that a transition did not cause a parallel change in combined benefit and functional floor. For example, the 2014–2015 transition was characterised by an increase in combined benefit and a significant decline in ecological floor. This highlights the necessity of a two-stage evaluation of annual transitions as a planning instrument.

6. Discussion

6.1. Green-space quantity and conversion yield

The first conclusion from the analysis is that green-space planning cannot confine itself to land quantity considerations. Xi'an's green-space scale increased significantly over the studied years, and the overall association between green-space scale and combined benefit was positive. However, the detailed transition record shows that this relationship was unstable for some specific intervals. Three positive scale-change intervals produced either ecological or combined-benefit weakness. Such cases demand moving beyond the green-space quantity account and focusing on benefit generation.

Our conclusion is supported by previous studies in green-space planning under densification and rapid green-space development. Ecological benefits depend on spatial configuration, ecological maturity, management practices, and adjacent built form [13, 46, 47]. Expanding hectares or increasing per-capita scale does not guarantee that the green space is generating the desired benefit. Thus, the Xi'an case provides a practical example of how adding green space leads to no ecological performance.

As far as conversion yield is concerned, we can clarify the interpretation of the 2017 peak year. While high in overall performance, the year also had the most productive annual transition. Transition 2016–2017 helped to improve socio-economic score and ecological score, raised the functional floor, and generated a significant increase in combined benefit. This explains the difference between annual and peak-year evaluations. For practical purposes, a high peak-year record should not be considered as a basis for planning because a more productive annual transition exists.

6.2. Ecological coordination as an organisational condition

The analysis of the ecological floor shows that ecological score needs to be decomposed. 2015 can be considered an acceptable year if measured only via overall ecological score or the combined score. But its humidification score is only 0.03, which made it the weakest ecological floor across the entire period. A planning organisation may ignore such issues when treating ecological benefit as a unified variable. Yet, moisture may depend on water availability in the soil, type of vegetation, evapotranspiration capability, irrigation, and meteorology.

Thus, the most successful ecological year was 2017, when cooling, humidification, oxygen release, and carbon fixation were all strong. We should not interpret this year as a perfect benchmark as ecological performance is likely to vary from year to year. Nevertheless, a high level of ecological coordination, rather than a dominant function, should be used as the criterion for analysing green space at high scales. A cooling-based ecological policy should also incorporate monitoring of moisture content and biogeochemical cycles.

Two following years show this conclusion. Humidification in 2018 was strong while cooling and biogeochemical functions had moderate scores. Oxygen release and carbon fixation in 2019 had strong scores while cooling and humidification were low. This implies that any year's ecological performance requires an adaptive management approach. Intervention measures should be adjusted each year depending on which ecological function is a bottleneck.

6.3. Socioeconomic improvements and ecological masking

Analysis of socioeconomic indicators provides another important observation. Tourism earnings, investment in public facilities, employment, wages, the number of active units, and service sector development improved substantially during the period. Thus, the city has been experiencing positive socio-economic benefit changes over time. For example, the 2017–2018 transition was productive for socio-economic benefit while ecological benefit declined sharply and total benefit went down. In other words, worsening ecological condition was buffered by socio-economic improvement, making it less noticeable.

However, this masking effect applies to many cases worldwide. Green spaces provide economic and public service gains in the form of visibility, amenity value, property values, tourism revenue, and investments in public facilities [7, 17, 31]. These benefits can be valuable, yet they are not necessarily associated with ecological performance. In order to meet the goals of heat moderation and moisture regulation, green space should be managed as ecological resources. Thus, any comprehensive analysis should consider domain movement separately.

Domain increment provides a simple solution. A positive combination of ΔS and ΔE shows that the city's green space is developing coherently. On the other hand, an increase in one domain and a decrease in the other indicate possible problems, especially in an expansion context. Xi'an had one such transition: 2017–2018 was characterised by a decline in ecological score while socio-economic benefit increased significantly. Thus, the planning strategy should involve monitoring socio-economic and ecological domains separately.

6.4. Implications for Xi'an's green-space development

As shown in Figure 7, our study allows deriving several practical conclusions about green-space development in Xi'an. As mentioned previously, the city needs to develop the high-scale range of 28.5-29.0 m^2/person. Our findings suggest, however, that green-space scale alone is not enough. Thus, we should ensure that conversion yield is sufficiently high. If a year with positive land addition does not lead to higher combined benefit and ecological score, we should investigate whether the land use is adequate, ecologically mature, and properly managed.

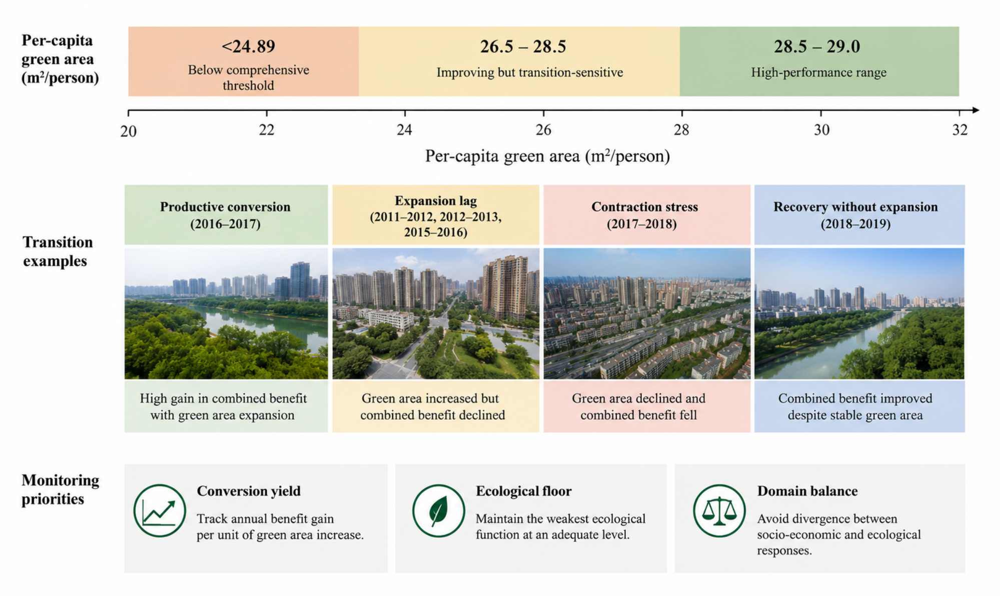


Figure 7. Planning synthesis.

Another important planning lesson is to pay attention to the ecological floor. It shows that an increase in green space can have a negative impact on ecological function. Xi'an's 2017 showed the highest overall ecological score with also the highest ecological floor and the most balanced components. Thus, the city needs to maintain this level of ecological performance. Every year, one of the functions can serve as the bottleneck. Thus, managers should select appropriate interventions aimed at resolving the identified problems.

Finally, the high level of socio-economic score indicates potential masking effects. Xi'an has had positive socio-economic changes every year during the examined period. Thus, we cannot rely solely on aggregate combined benefit. Instead, we need to examine the annual movements in socio-economic and ecological domains. This should be considered as a general rule in Xi'an green-space planning.

6.5. General applicability and limitations

The current analysis of green-space conversion can be applied in other cities. In order to conduct similar research, one needs to have annual values of the scale variable, socio-economic and ecological scores, combined score, and ecological functions. The conversion method can be applied also to districts. In this case, city-level averages can mask neighbourhoods' inequalities, accessibility, and heat burden. Future applications should also use spatially explicit canopy data, land surface temperatures, park accessibility, and resident-use indicators.

Several limitations of the current analysis should be mentioned. First, there are only eleven annual states and ten transitions in the current dataset, which limits causal inference in favour of strategic evidence. Second, annual scores may depend on the weather, policies, measurements, and changes in data recording procedures. The component floor only tells us whether there is a bottleneck in ecological functions but does not provide any physical reasons behind it. Thus, future work should combine the proposed transition method with spatial data.

The third drawback concerns socio-economic domain. This domain is composite, including factors related to tourism, employment, public facility management, investments, real estate development, noise levels, green area of the city, green coverage, green area production rate, and service sector. Although these factors are important, not all of them measure socio-economic benefits and public services equally well. Future research should introduce accessibility and equality variables so that the analysis is conducted from the public perspective.

Nevertheless, the present study introduces a powerful tool to analyse annual green-space transitions from the perspective of benefit conversion. We know whether land addition was efficient, whether benefit was lost during green space expansion, whether socio-economic benefits masked ecological degradation, and whether ecological functions were coordinated. This is useful for urban planning because these questions address important issues of implementation.

7. Conclusion

The current paper aimed to understand the conversion or loss of green-space benefits in Xi'an due to the annual changes in green-space scale, built-up pressure, and ecological function composition. Based on a nine-year annual dataset, it revealed that green-space performance was driven by transition quality rather than just green-space scale. Although the scale increased considerably and overall benefit improved, the analysis of individual years showed that land addition could fail to generate immediate comprehensive benefit.

According to the analysis, five intervals represented productive conversion, three indicated expansion lag, one implied contraction stress, and one showed recovery with no green space addition. The most productive transition was 2016–2017, with an increase in per-capita green area of 1.70 m^2/person, socio-economic and ecological scores of 0.21 and 0.18 respectively, and combined benefit of 0.20. The yield of the transition was 0.118 score points per one added m^2/person, which is the record-high value. Contrastively, two other intervals had positive land additions while their socio-economic or ecological score went down. Finally, in 2017–2018, socio-economic improvement was accompanied by an ecological score decline.

In terms of function composition, the ecological floor provided the major functional explanation. The most balanced composition was seen in 2017, when the minimum score of components was 0.69 and all four functions performed well. In 2015, the year acceptable overall eco-score-wise, the minimum score of humidification was 0.03, and the difference between the maximum and minimum was the highest in the dataset. Thus, the aggregate score would provide a misleading indication of the ecological completeness in this year.

Given the above, for Park City planning in Xi'an, it is recommended to monitor annual benefit conversion rather than green-space quantity. Specifically, each transition should be evaluated according to the change in socio-economic, ecological, and combined score. High-scoring years should also be assessed in terms of minimum score in ecological functions. Xi'an's planning strategy should therefore aim to maintain the high-scale range of 28.5–29.0 m^2/person and avoid low ecological floor in green spaces.

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