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Evaluating urban park ecosystem services and modeling improvement scenarios

Nuanchan Singkran

Faculty of Environment and Resource Studies, Mahidol University, 999 Moo 5, Sai 4 Phuttamonthon Rd., Salaya, Phuttamonthon, Nakhon Pathom 73170 Thailand

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ABSTRACT

Three ecosystem services of the 25 public parks in Bangkok, including carbon sequestration, avoided runoff, four air pollutant removals (CO, NO_2, PM_{10}, and $PM_{2.5}$), and the relevant monetary values, were determined using i-Tree Eco software. Two modeling scenarios (MS) including MS1 (no greening improvement) and MS2 (improvement by increasing either green area or tree planting, or both in the parks) with tree annual mortality rates (AMR) of 1 and 3% were developed to forecast the parks' ecosystem services for 50 years after 2020 (2021–2071). The results revealed the synergistic interactions of the different tree planting specifications (MS1 and MS2) and tree mortality rates on the parks' ecosystem services. For MC2 with the assigned 1% AMR, the parks' optimal ecosystem services were obtained and the average annual monetary value (0.55 million USD) of the total ecosystem services of the 25 parks over the 50-year forecast was 150% higher than that (0.22 million USD) in 2020. Based on MS1 and MS2, tree rotations should be conducted in the parks after 2057 and 2065, respectively, for the low tree AMR ($\leq$1%) but not later than 2041 and 2043, respectively, for the higher tree AMR.

1. Introduction

In Bangkok, the capital of Thailand and one of the world's crowded megacities, it is rather difficult for urban dwellers to find peaceful and spacious spaces for taking a break from work, refreshing their souls, exercising, and engaging in other activities. Nevertheless, public parks scattered across Bangkok appear to be valuable greening assets that provide ecosystem services to people from all walks of life. The ecosystem services provided by urban green areas have been well recognized in terms of their environmental and societal benefits, such as reducing noise and air pollutants, regulating floods and the microclimate, and promoting health, recreation, aesthetics, and urban biodiversity [1–9].

Like other megacities worldwide in the 21st century, Bangkok has been facing climate change problems due to intensive human activities that have caused a large amount of greenhouse gas emissions, approximately 46.44 million tons of carbon dioxide equivalent (t-CO_2e). However, the total green area (excluding agricultural areas) in Bangkok has the ability to absorb only approximately 49,279 t-CO_2e [10] or 0.1% of the total amount emitted. This is because approximately 99% of the 1569 km^2 area in Bangkok was overwhelmed with anthropogenic activities that emitted large amounts of greenhouse gases, i.e., 14.91, 26.85, and 4.73 million t-CO_2e from transportation, energy, and waste-related management sectors, respectively [10,11].

Although the greenhouse gas reduction provided by green areas in Bangkok is small compared to the amount emitted in the city, these urban green areas, specifically public parks, are still important carbon sinks and ecosystem service providers [12–15]. Hence,

E-mail address: nuanchan.sin@mahidol.edu.

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both the quantity and quality of greening management are crucial for improving the carbon sequestration (C_{seq}) potential and that of other urban ecosystem services of green areas. Currently, there are 39 major public parks distributed across Bangkok with an approximate area of 6.44 km^2 in total [16]. A recent study reported that 25 of these public parks had great potential for providing ecosystem services and had the ability to absorb approximately 41,219.4 t-CO_2 in 2020 or 83.6% of the total amount (49,279 t-CO_2e) absorbed by the city's greening sector [11].

Key variables for urban greening management, whereas green areas are often limited by the domestic sector and urbanization [11], are proper tree planting specification, stewardship, and maintenance. These variables not only help urban trees reach maturity but also reduce the tree mortality rate and improve their ecosystem services [17–20]. Urban trees tend to have a high mortality rate during the early period after planting. However, their mortality rates vary in space and time depending on various variables, such as the taxa and age of the planted trees, stewardship and maintenance, and the occurrence of unexpected environmental crises or pest outbreaks. The tree rotation period is another key variable for maintaining the optimal ecosystem services of urban trees over time [19,20].

The objectives of this study were thus to determine how greening management of the 25 parks could improve the parks' three ecosystem services and the relevant monetary benefits of the parks over time through modeling scenarios (MS). The three forecasted ecosystem services were C_{seq}, avoided runoff (AR), and critical air pollutant removals (AP_{rem}), including carbon monoxide (CO), nitrogen dioxide (NO_2), and particulate matter less than 10 (PM_{10}) and 2.5 ($PM_{2.5}$) microns. The MS results were useful for preparing specific greening management plans to improve park ecosystem services.

2. Materials and methods

2.1. Park locations and surrounding environment

Bangkok is situated between 13° 30′ N, 100° 20′ E and 13° 58′ N, 100° 58′ E and is governed by the Bangkok Metropolitan Administration (BMA). The capital of Thailand covers 50 districts with 5,494,932 individuals of registered population in 2022 [21], excluding a large nonregistered population that temporarily resides in Bangkok for various purposes e.g., working, studying, or visiting [11]. The 25 major public parks are distributed across 16 districts (Fig. 1). Seven districts contain more than one of these parks, including Bang Khen (Parks 14 and 20), Bueng Kum (Parks 5 and 11), Chatuchak (Parks 3, 6, and 8), Khlong Sam Wa (Parks 9 and 21), Khlong Toei (Parks 7 and 23), Lad Krabang (Parks 16 and 17), and Parwet districts (Parks 1, 2, and 18). The remaining nine districts

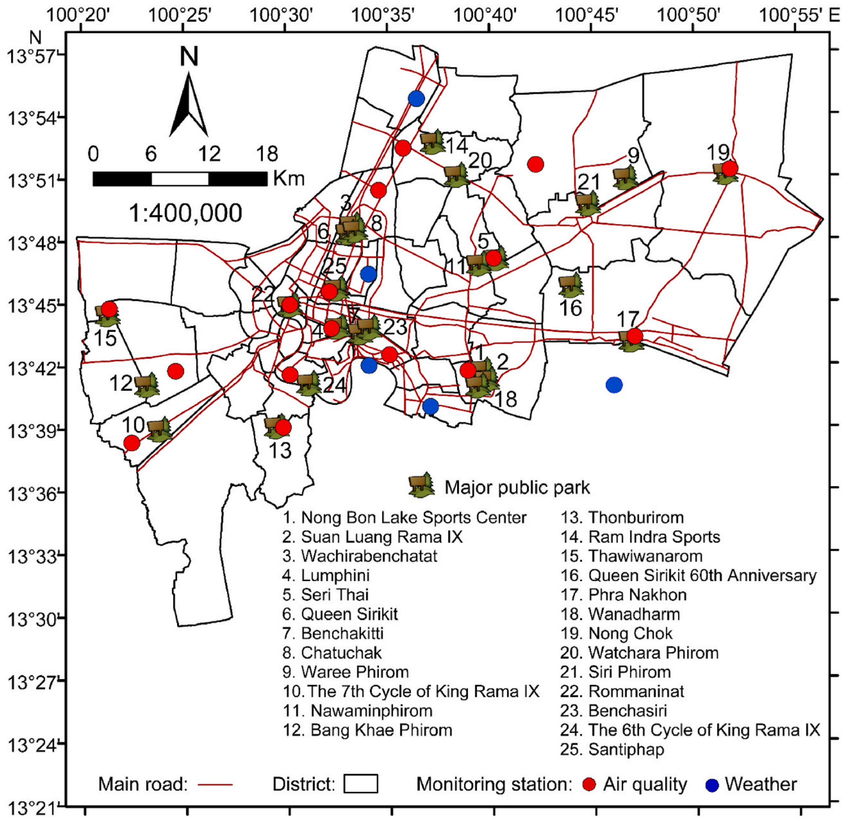

Fig. 1. Twenty five major public parks and monitoring stations of air quality (16 stations) and weather (five stations) in Bangkok and nearby areas (BMA; TMD, unpublished data).

have only one major public park per district (Fig. 1). Bangkok is rather small, comprising approximately 1569 km^2, so it is possible to travel across the city in a single day. Consequently, the 25 parks serve not only people who reside in the 16 districts in which these parks are located but also visitors.

The BMA's air quality monitoring stations were installed in the 16 districts (one station per district). Five weather monitoring stations of the Thai Meteorological Department (TMD) are located in the central, eastern, northern, and southern parts of Bangkok (Fig. 1). The AP and weather data from the monitoring stations in or near a district were used for MS for the park(s) located in that district. Like that of many provinces in the country, the climate in Bangkok is tropical with three seasons a year that are influenced by the northeast and southwest monsoons including summer (February–April), rainy (May–October), and winter (November–January). With sunlight throughout the year, the ranges of mean minimum and maximum temperatures in Bangkok are 27–35 °C, 26–32 °C, and 22–31 °C in the summer, rainy, and winter seasons, respectively. The mean monthly cumulative rainfalls are 10–60 millimeters (mm), 106–203 mm, and 6–57 mm in the summer, rainy, and winter, respectively [22,23].

2.2. Ecosystem service determination and data used

The parks' three ecosystem services (C_{seq}, AR, and four AP_{rem}) in 2020 were determined using i-Tree Eco software [24]. The tree input data included the observed amounts (numbers) and species of trees in group 1 (excluding palms) with a height of at least 1.3 m aboveground and their diameters at breast height (DBH) in each of the 25 parks in 2020 in Singkran [11] (Online Resource 1). Palms were not included in this study because of their low C_{seq} potential in the 25 parks compared to that of the group 1 trees in the same dimension and tree quantity [11]. The environmental input data were the hourly observed data across 2020 of weather variables (air temperature, precipitation, pressure, solar radiation, and wind speed and direction) at the five monitoring stations of the TMD (unpublished data) and the four air pollutants at the 16 monitoring stations of the BMA (unpublished data). These environmental data were aggregated in the i-Tree database to execute i-Tree Eco for estimating trees' C_{seq}, AR, and AP_{rem} in the studied parks.

2.3. Modeling scenario development

The observed numbers and species of trees in 2020 and their relevant proposed values are shown in Table 1, following the suggested baseline values for the 25 parks in Singkran [11, p.12]. These data were used to develop two MS for forecasting which conditions would maximize the parks' three ecosystem services over time. These included MS1 (no greening improvement; based on the observed

Table 1
The green and other areas, observed numbers of trees and associated species in the 25 public parks in 2020, and the relevant proposed amounts for greening improvement of the parks.

Park name	Area (ha)[a]		No. of trees by subgroup[b]					Total trees	No. of species by subgroup[c]					Total species
	Green	Others	1	2	3	4	5		1	2	3	4	5	
1. Nong Bon Lake Sports Center														
Observed	22.2	85.7	953	184	2525	57	326	4045	7	6	23	3	7	46
Proposed	56.6	51.3	2547	1924	5321	623	3736	14,151	57	56	46	16	57	232
2. Suan Luang Rama IX														
Observed	44.4	35.6	606	306	1227	102	890	3131	42	30	91	19	49	231
Proposed	44.4	35.6	1998	1510	4174	489	2931	11,102	92	80	112	32	103	419
3. Wachirabenchatat														
Observed	39.1	22.0	1028	2513	2120	360	1396	7417	13	20	39	2	13	87
Proposed	39.1	22.0	1760	2513	3676	431	2581	10,961	63	20	60	15	63	221
4. Lumphini														
Observed	33.7	23.9	786	479	2662	48	2490	6465	16	18	45	3	42	124
Proposed	33.7	23.9	1517	1146	3168	371	2490	8692	66	68	65	16	42	257
5. Seri Thai														
Observed	4.7	6.4	898	550	1375	123	1604	4550	24	30	52	5	37	148
Proposed	5.8	5.3	898	550	1375	123	1604	4550	24	30	52	5	37	148
6. Queen Sirikit														
Observed	21.6	9.9	149	744	370	22	1468	2753	25	19	46	3	41	134
Proposed	21.6	9.9	972	744	2031	238	1468	5453	75	19	68	16	41	219
7. Benchakitti														
Observed	8.2	13.5	55	149	1139	17	384	1744	12	16	31	2	35	96
Proposed	11.4	10.3	513	388	1139	126	753	2919	62	66	31	15	85	259
8. Chatuchak														
Observed	17.5	7.4	597	1015	1030	81	561	3284	16	24	44	3	22	109
Proposed	17.5	7.4	788	1015	1645	193	1155	4796	66	24	66	16	72	244
9. Waree Phirom														
Observed	17.3	8.4	15	95	717	161	66	1054	2	2	18	2	5	29
Proposed	17.3	8.4	779	589	1627	191	1142	4328	52	52	42	15	55	216
10. The 7th Cycle of King Rama IX														
Observed	9.8	6.2	125	370	1087	147	249	1978	6	10	15	4	9	44

(continued on next page)

Table 1 (*continued*)

Park name	Area (ha)[a]		No. of trees by subgroup[b]					Total trees	No. of species by subgroup[c]					Total species
	Green	Others	1	2	3	4	5		1	2	3	4	5	
Proposed	9.8	6.2	441	370	1087	147	647	2692	56	10	15	4	59	144
11. Nawaminphirom														
Observed	4.0	10.9	125	113	442	61	223	964	22	18	39	5	28	112
Proposed	7.8	7.1	351	266	734	86	515	1952	72	68	60	18	78	296
12. Bang Khae Phirom														
Observed	8.3	2.5	159	160	842	191	501	1853	9	8	19	3	18	57
Proposed	8.3	2.5	374	283	842	191	548	2238	59	58	19	3	65	204
13. Thonburirom														
Observed	6.8	3.3	380	223	625	113	387	1728	24	34	55	12	41	166
Proposed	6.8	3.3	380	232	640	113	449	1814	24	42	69	12	91	238
14. Ram Indra Sports														
Observed	8.8	0.7	1135	26	768	1	483	2413	9	4	23	1	11	48
Proposed	8.8	0.7	1135	300	828	97	581	2941	9	54	46	14	61	184
15. Thawiwanarom														
Observed	6.6	2.0	87	126	324	172	1149	1858	3	6	15	3	9	36
Proposed	6.6	2.0	297	225	621	172	1149	2464	53	56	39	3	9	160
16. Queen Sirikit 60th Anniversary														
Observed	3.6	4.8	51	106	360	50	128	695	9	9	20	2	15	55
Proposed	4.4	4.0	198	150	414	50	291	1103	59	53	43	2	65	222
17. Phra Nakhon														
Observed	5.4	2.6	200	148	211	23	133	715	10	8	12	1	9	40
Proposed	5.4	2.6	243	184	508	60	357	1352	53	44	37	14	59	207
18. Wanadharm														
Observed	2.7	2.2	126	87	116	51	314	694	7	8	21	3	12	51
Proposed	2.7	2.2	126	92	254	51	314	837	7	13	46	3	12	81
19. Nong Chok														
Observed	3.4	2.5	117	181	250	39	150	737	5	14	21	3	16	59
Proposed	3.4	2.5	153	181	320	39	225	918	41	14	45	3	66	169
20. Watchara Phirom														
Observed	3.9	1.5	35	129	794	81	394	1433	6	12	24	2	11	55
Proposed	3.9	1.5	176	133	794	81	394	1578	56	16	24	2	11	109
21. Siri Phirom														
Observed	2.7	0.7	17	46	121	45	96	325	3	4	13	2	13	35
Proposed	2.7	0.7	122	92	254	45	179	692	53	50	37	2	63	205
22. Rommaninat														
Observed	2.8	2.0	63	69	249	9	160	550	14	14	31	3	21	83
Proposed	2.8	2.0	126	96	264	31	185	702	64	41	46	16	46	213
23. Benchasiri														
Observed	2.2	2.4	171	87	268	10	122	658	12	9	21	2	22	66
Proposed	2.4	2.2	171	87	268	27	159	712	12	9	21	15	59	116
24. The 6th Cycle of King Rama IX														
Observed	3.4	2.1	45	126	384	14	110	679	11	18	47	2	18	96
Proposed	3.4	2.1	153	126	384	38	225	926	61	18	47	15	68	209
25. Santiphap														
Observed	1.5	1.7	331	59	246	20	69	725	10	8	26	2	17	63
Proposed	1.7	1.5	331	59	246	20	113	769	10	8	26	2	61	107

[a] Green area (one ha = 0.01 km^2) proposed for each park was increased to match the baseline value (i.e., 52.5 % of the total area of that park) suggested by Singkran [11]. It was the same as the observed one if it was consistent with or greater than the suggested proportion.

[b] No. (numbers) of trees by subgroup proposed for each park were increased, so that their density equaled the baseline values suggested by Singkran [11], i.e., 45, 34, 94, 11, and 66 trees per ha of green area in the park for subgroups 1, 2, 3, 4, and 5, respectively. They were the same as the observed ones if their density in that subgroup was consistent with or greater than the suggested density. The five tree subgroups were (1) hill/dry evergreen forests, (2) rainforest, (3) deciduous dipterocarp/mixed deciduous forests, (4) mangrove forest, and (5) beach forest and others – trees with varied rainfall preferences, e.g., dry, moist, or wet.

[c] No. of species by tree subgroup for additional planting in the parks for improvement were selected using i-Tree Species software [25]. The list of the selected tree species and the relevant parks for planting are provided in Online Resource 2.

data in 2020) and MS2 (either green area or tree planting, or both were improved in certain parks; based on the proposed data) with the assigned tree annual mortality rates (AMR) of 1 and 3% for the parks. Each MS was forecasted for 50 years using i-Tree Eco, starting from year 0 (2020; the year that the observed tree-related data were available) and ending in 2071 (the 50th year). Located in a tropical climate region, the year-round growth of trees in the 25 parks was modeled (i.e., 365 days without an annual frost).

No tree mortality study was conducted in the 25 parks. However, the BMA's Public Park Office (personal communication) unofficially estimated that the tree AMR in these parks were between 1% in general and not more than 3% for the worst condition, which hardly occurred in the parks. These assigned tree AMR were in the same range (1.5–2.9% AMR) of most tree species under irrigated conditions in urban tree planting programs in Florida [19, pp. 658–659], which has a similar climate to Thailand. In general, urban tree mortality rates vary by biophysical variables, such as taxa and age of trees, site characteristics, and environmental conditions, and human-related variables, such as maintenance, stewardship, disease, and pests [20].

For MS2, i-Tree Species software [25] was used to select tree species for additional planting in the parks for greening improvement (see the proposed values in Table 1). The software computed the percentage suitability (0–100%) of a tree species for planting in the parks according to specific criteria for this study. These included the local climatic details of the study location (i.e., Bangkok) and functional ability (scores of at least 8 out of 10, with 10 being the best) of a tree species, based on the following: (1) removal of CO, NO_2, PM, and sulfur dioxide, (2) low emissions of volatile organic compounds, (3) carbon storage, and (4) reduction of ultraviolet radiation. The list of tree species and their suitability was obtained from the software computation. In this study, only the top 10–50% tree species (i.e., tree species with at least 50% suitability for planting in the study location) were selected for additional planting in parks for improvement (see the selected tree species and relevant parks in Online Resource 2) with their initial simulated DBH of 2 cm as young trees. The same tree species that already existed in a park were excluded from MS2 for that park.

The i-Tree Eco software was used to determine the three ecosystem services of the 25 parks in 2020 based on the relevant observed data in the same year in Singkran [11] and simulate each MS over the 50 forecasted years after 2020 (2021–2071). The densities (amount ha^{-1} of green area) of the trees' C_{seq} ($C_{seq\text{-}den}$), AR (AR_{den}), and AP_{rem} ($AP_{rem\text{-}den}$) were estimated for each park. This software has been widely used for modeling the structures and functions of urban trees and forecasting their ecosystem services [26–35]. Although i-Tree Eco is favored by researchers in related fields, modeling discrepancies may occur for some reasons, e.g., applying improper allometric equations or conversion factors, different scales of pollutant dispersion, and physiological variations in the same tree species in different climatic regions [28,29,36]. However, these variances are trivial as long as the local input data are adequate for i-Tree Eco to utilize the local standardized data for the model estimates [12,30,37].

According to i-Tree Eco, the trees' C_{seq} values were derived from their estimated biomass (including both aboveground and belowground amounts) using relevant allometric equations [24]. The AR of each park was computed based on tree cover area in the park, impervious cover beneath trees (including trees' root systems), and the TMD's hourly observed weather data at the monitoring station located near the park. The AP_{rem} of each park was computed regarding gas exchanges, particulate matter interception by trees for each of the four air pollutants in the park, and the hourly observed data of the TMD's weather and the BMA's concentrations of the four air pollutants at the monitoring stations located close to the park. The unobserved values, comprising tree cover area, impervious cover beneath trees, gas exchanges, and particulate matter interception by the trees in each park, were estimated by the software's relevant equations and characteristics of the observed tree species. Details of the equations and variables for computing C_{seq}, AR, and AP_{rem} are available in Refs. [38–40].

3. Results and discussion

3.1. Park ecosystem services in 2020

The total estimated amounts of C_{seq}, AR, and AP_{rem} of all parks in 2020 were 800.7 t-C, 4726.6 m^3, and 7273.7 kg, respectively, whereas their total estimated values of all parks were 216,512.4 USD. The monetary density by park was consistent with the park's ecosystem service density (Table 2). Park ecosystem services are influenced by both the density and species diversity of planted trees, which are related to their DBH and canopy structure [8,11,41,42]. The species, DBH, and crown health of trees directly influenced the trees' C_{seq} and indirectly influenced the trees' AR and AP_{rem}, whereas tree cover and pollutant concentration directly influenced the trees' AR and AP_{rem} [6,8,11,43]. The highest $C_{seq\text{-}den}$ (19.6 t-C ha^{-1}), AR_{den} (119.1 m^3 ha^{-1}), and $AP_{rem\text{-}den}$ (143.4 kg ha^{-1}) detected at Park 5 (Table 2) were consistent with the highest tree density (4550/4.7 = 968 trees ha^{-1} of green area, Table 1) observed at this park.

Of the 459 tree species observed from the 25 parks in 2020 [11, Online Resource 1], the species richness varied by park due to different sizes of green areas, designs, functions, and other features of the parks. However, the common planted species in these parks were mainly similar except in Parks 2 and 6, where diverse exotic species were collected for studying and conserving purposes. Diverse tree taxa reflected the trees' characteristics, such as DBH, height, leaf area, and crown width, when they were full-grown. These variables influenced the trees' capacities for $C_{seq\text{-}den}$, AR_{den}, and $AP_{rem\text{-}den}$ in the parks.

Many trees in the 25 parks had DBH between 7.6 and 30.5 cm (26–34.6% on average), except in Park 6, where 80.4% of the trees were small (DBH <7.6 cm). Less than 10% of the trees in all parks had DBH larger than 45.7 cm (Table 2). The small and middle-sized trees in the parks had the potential to grow and maximize the parks' ecosystem services. Thus, tree rotations (removal and replanting) in the parks should be performed within an appropriate period, i.e., not before the trees reach maturity with large DBH, crown width, and tree cover and not too long after the trees are old and their ecosystem service functions have declined [6,8,11]. The canopy structure and leaf area of urban trees contribute to air pollution mitigation as air pollutant filters, while the uptake and transpiration processes of trees can reduce urban runoff of storm waters [6,8,43].

Tree mortality in parks is another variable affecting park ecosystem services. The more healthy trees the parks have, the greater the ecosystem services the parks provide. The mortality of urban trees is influenced by human-related variables (such as maintenance, stewardship, pests, and disease) and biophysical variables (such as taxa and age of the trees, environmental conditions, and characteristics of planted areas) [20,44]. According to the routine stewardship and maintenance of the BMA, the trees in the 25 parks were mainly in good health. Under normal circumstances, the AMR of young trees ($\leq$5 years old) in the parks was 1–3%, and it was not more than 1% for the older trees (BMA's Public Park Office, personal communication).

Table 2
The estimated cover and distribution by diameters at breast height (DBH) of trees, total amounts and densities of carbon sequestration (C_{seq}), avoided runoff (AR), air pollutant removal (AP_{rem}), and momentary value of each park in 2020.

Park code	Tree cover (%)	Tree distribution (%) by DBH (cm)					C_{seq} (t-C)		AR (m^3)		AP_{rem} (kg) by type				AP_{rem} (kg)		Values[b] (USD)	
		<7.6	7.6–15.2	15.3–30.5	30.6–45.7	>45.7	Total	Density[a]	Total	Density	CO	NO_2	PM_{10}	$PM_{2.5}$	Total	Density	Total	Density
1	58.0	19.6	8.9	38.7	32.4	0.4	70.4	3.2	117.8	5.3	78.5	136.1	450.8	4.6	669.9	30.2	18,411.9	829.4
2	20.4	17.6	30.4	40.3	7.5	4.2	47.7	1.1	168.0	3.8	55.2	142.4	451.7	6.3	655.6	14.8	14,310.9	322.3
3	49.1	6.4	47.4	32.7	13.3	0.2	87.5	2.2	428.7	11.0	75.3	157.7	658.2	8.5	899.7	23.0	24,107.8	616.6
4	62.9	22.3	24.8	25.0	23.7	4.2	112.6	3.3	1223.0	36.3	155.6	375.5	712.6	30.5	1274.2	37.8	33,743.7	1001.3
5	100	7.7	18.4	49.6	16.2	8.1	92.0	19.6	559.6	119.1	64.4	169.9	427.2	12.7	674.2	143.4	23,742.8	5051.7
6	12.7	80.4	8.2	7.7	2.9	0.8	14.4	0.7	61.1	2.8	10.7	22.5	93.8	1.2	128.2	5.9	3795.1	175.7
7	94.3	8.3	15.0	16.6	51.0	9.1	45.5	5.5	92.6	11.3	46.8	61.0	99.0	2.4	209.1	25.5	10,239.4	1248.7
8	74.1	9.9	14.5	29.1	43.7	2.8	61.9	3.5	324.9	18.6	50.9	113.6	471.7	6.5	642.7	36.7	17,168.5	981.1
9	10.4	22.0	46.4	27.7	2.8	1.1	10.7	0.6	90.5	5.2	6.9	17.5	43.1	1.5	69.0	4.0	2742.4	158.5
10	41.8	32.0	33.4	24.3	6.3	4.0	23.5	2.4	79.3	8.1	17.4	50.5	91.9	3.0	162.8	16.6	5869.3	598.9
11	64.9	13.6	31.1	43.2	9.4	2.7	14.5	3.6	100.2	25.1	10.2	28.7	73.1	2.3	114.2	28.6	3841.8	960.4
12	42.4	31.8	38.7	23.6	3.5	2.4	18.6	2.2	50.0	6.0	15.0	37.0	31.8	1.9	85.7	10.3	4282.8	516.0
13	84.1	15.9	16.8	49.1	15.5	2.7	32.9	4.8	129.9	19.1	24.3	77.3	165.9	3.6	271.1	39.9	8600.8	1264.8
14	100	0.4	1.1	78.0	19.7	0.5	54.2	6.2	515.1	58.5	37.2	104.5	309.9	9.8	461.4	52.4	14,906.9	1694.0
15	40.5	53.2	18.0	22.9	5.6	0.3	13.0	2.0	65.8	10.0	11.4	30.2	40.5	1.4	83.5	12.7	3403.6	515.7
16	56.5	7.2	24.2	61.2	4.2	3.2	10.5	2.9	87.9	24.4	12.1	25.1	37.3	1.0	75.5	21.0	2745.3	762.6
17	49.7	6.4	18.2	39.5	33.7	2.2	12.9	2.4	118.8	22.0	16.0	35.2	51.8	1.4	104.4	19.3	3504.8	649.0
18	53.7	37.3	20.5	33.9	6.6	1.7	6.1	2.3	25.3	9.4	8.8	22.1	69.8	0.9	101.7	37.7	1980.2	733.4
19	48.6	31.9	21.8	22.4	22.1	1.8	8.3	2.4	71.5	21.0	9.8	20.6	53.9	0.8	85.1	25.0	2359.9	694.1
20	76.4	28.8	32.9	26.3	11.9	0.1	17.2	4.4	155.7	39.9	11.5	31.0	92.2	2.8	137.6	35.3	4639.1	1189.5
21	20.0	20.0	54.5	24.3	0.6	0.6	2.6	1.0	26.4	9.8	2.1	4.9	12.2	0.4	19.6	7.2	701.2	259.7
22	69.7	14.4	16.5	48.0	18.7	2.4	10.5	3.8	54.6	19.5	12.9	26.4	28.8	1.3	69.4	24.8	2634.7	941.0
23	81.7	9.4	41.3	36.0	9.3	4.0	8.9	4.0	55.5	25.2	10.9	23.5	35.2	1.4	71.0	32.3	2337.2	1062.4
24	70.4	20.6	13.4	33.7	23.6	8.7	12.6	3.7	55.7	16.4	10.2	32.8	83.0	2.4	128.4	37.8	3480.2	1023.6
25	100	3.2	53.2	30.6	10.1	2.9	11.6	7.8	68.7	45.8	13.0	30.1	35.1	1.6	79.8	53.2	2962.2	1974.8
						Total	800.7	–	4726.6	–	767.2	1776.0	4620.3	110.2	7273.7	–	216,512.4	–

[a] Density = amount of each ecosystem service ha^{-1} of green area; one ha = 0.01 km^2.
[b] Values: C_{seq} = 188 USD $(t\text{-}C)^{-1}$, AR = 2.36 USD $(m^3)^{-1}$, CO = 1.54 USD kg^{-1}, NO_2 = 10.84 USD kg^{-1}, PM_{10} and $PM_{2.5}$ = 7.24 USD kg^{-1}.

3.2. Park ecosystem services in 50 forecasted years

Over the 50-year forecast of both MS, the maximum density of each ecosystem service of each park with the assigned tree AMR of 1% was greater than that obtained with the assigned tree AMR of 3% and the time spent to attain the maximum ecosystem service was longer. The parks' three ecosystem services reached the maximum densities in certain years (as indicated above the bar graphs in Fig. 2) during the 50-year forecast before declining afterward. For the assigned tree AMR of 1%, the maximum $C_{seq\text{-}den}$ were detected earliest in the 21st year at Park 9 (MS1) and in the 28th year at Park 6 (MS2), slowest in the 50th year at some parks (e.g., Parks 10, 20, 23, and 25), and between the 23rd – 49th years at the remaining parks of both MS (Fig. 2a). The parks took longer times to provide the maximum AR_{den} (36–50 years, Fig. 2c) and $AP_{rem\text{-}den}$ (47–50 years, Fig. 2e). For the assigned tree AMR of 3%, the maximum $C_{seq\text{-}den}$

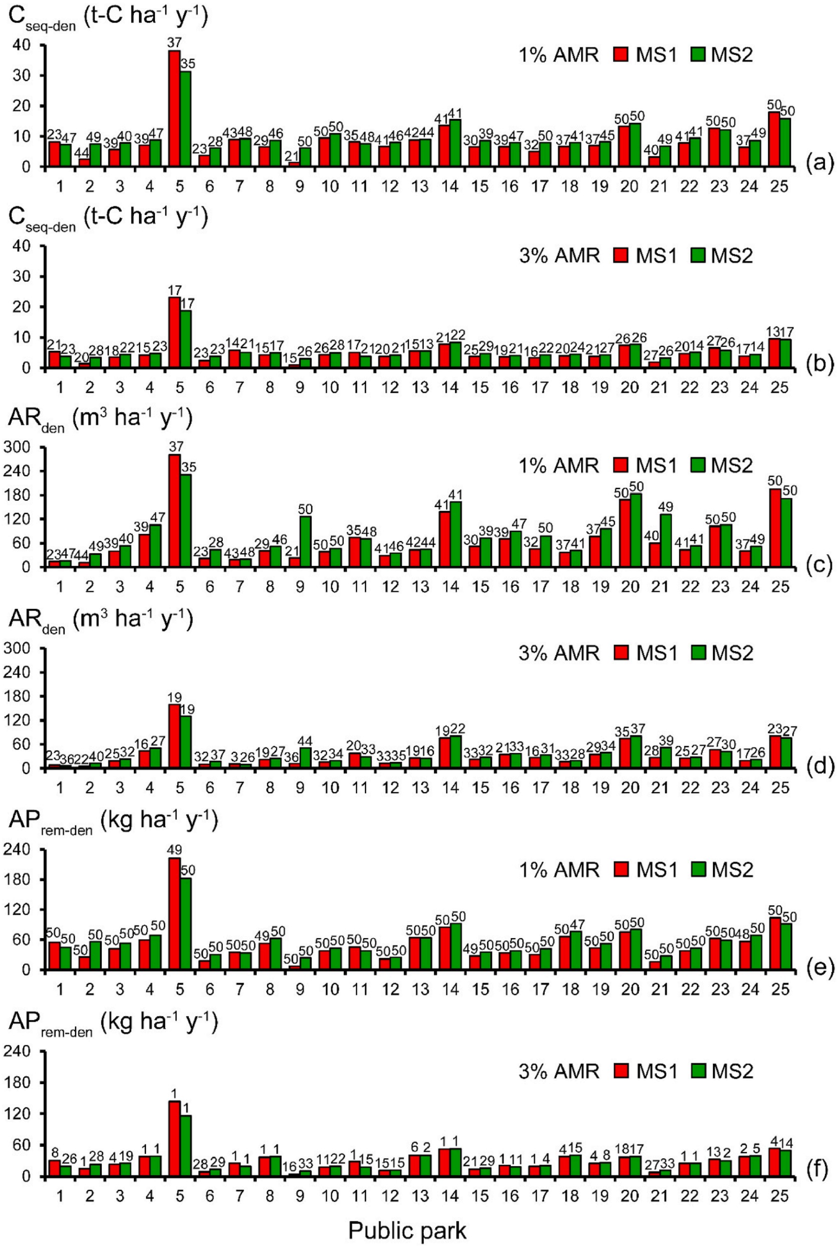

Fig. 2. The maximum densities of carbon sequestration ($C_{seq\text{-}den}$), avoided runoff (AR_{den}), and air pollutant removal ($AP_{rem\text{-}den}$) in certain years after 2020 (as indicated above the bar graphs) in Parks 1–25 obtained from modeling scenarios (MS) 1 (no greening improvement) and 2 (greening improvement) with the assigned tree annual mortality rates (AMR) of 1 and 3% for each MS.

(Fig. 2b), AR_{den} (Fig. 2d), and $AP_{rem\text{-}den}$ (Fig. 2f) at many parks were detected between the 14^{th} – 28^{th}, 16^{th} – 40^{th}, and 1^{st} – 15^{th} years, respectively, for both MS.

The parks' optimal ecosystem services were obtained from MS2 (greening improvement) with the assigned tree AMR of 1%. The MS revealed the synergistic interactions of the different tree planting specifications and tree mortality rates that resulted in varied influences on the parks' ecosystem services. The maximum $C_{seq\text{-}den}$ detected within the 50-year forecast in MS2 were 3.1–325.1% and 0.4–174.5% with assigned tree AMR of 1 and 3%, respectively, higher than those in MS1 (no greening improvement). For some parks in MS2, the increase in green area alone at Park 5 or both green area and some trees planted at Parks 1, 11, 23, and 25 caused the maximum $C_{seq\text{-}den}$ of these parks to be lower than those in MS1 (Fig. 2a). This was because increasing green area immediately reduced the tree density, but additional planting of some small trees (DBH = 2 cm for the initial simulated year of 2020) took time for the surviving trees to mature. The latter two ecosystem services of the parks showed similar patterns, as discussed below.

The maximum AR_{den} detected within the 50-year forecast in MS2 were 2.2–448% and 6.4–335.6% for the assigned tree AMR of 1 and 3%, respectively, higher than those in MS1, but the values of some parks for both tree AMR (e.g., Parks 5, 11, and 25) were lower than those in MS1 (Fig. 2c–d). The maximum $AP_{rem\text{-}den}$ of many parks in MS2 were 6.8–213.7% and 1.3–124.1%, for the assigned tree AMR of 1 and 3%, respectively, higher than those in MS1, whereas the values of some parks for both tree AMR (e.g., Parks 1, 5, 7, 11, 13, 23, and 25) were lower than those in MS1 (Fig. 2e–f). Although the BMA applied the same management procedures on urban trees' stewardship and maintenance to the 25 parks, the local variations in species, size/age, and environmental tolerance of the planted trees among the parks were unavoidable. These may affect the trees' growth cycles and health conditions and, in turn, influence the trees' capacities for surface runoff reduction via their uptake and transpiration processes and air pollutant absorptions through their leaf stomata at different rates over time [6,8,43].

The total amounts of each ecosystem service for the 50 forecasted years of Parks 1–4, 6–9, and 14, where the planting of many young trees in 2020 was simulated (MS2), were obviously higher than those in MS1 (no greening improvement) for both assigned tree AMR. In contrast, the total amounts of each ecosystem service of the remaining parks (Parks 5, 10–13, and 15–25) with little greening improvement (MS2) were slightly higher than those in MS1 (Fig. 3a–f). These results indicated that the increase in either green area or the low amounts of planted trees, or both in some parks reduced the parks' ecosystem service densities in short periods. However, in the long term, the parks' ecosystem services were maximized when the surviving trees in the parks were mature [14,41,42].

Not only greening improvement but also tree rotation period were key variables for maintaining the parks' optimal ecosystem services over time. The tree rotation period was a site-specific variable and varied park by park. In general, tree rotation in a park is conducted to remove dead, unhealthy, or old trees that passed their maturity and replant new/young trees. The maturity of a tree can be indicated by the tree C_{seq} capacity, i.e., the older the tree is, the lower the carbon amount sequestered by the tree [12,15]. Thus, over the 50-year forecast in this study, the mature period of the tree community in each park was the remaining years in which the park's $C_{seq\text{-}den}$ declined after attaining its maximum value in a previous year. Meanwhile, the different periods in which the parks attained the maximum ecosystem service densities reflected the influences of tree AMR on tree maturity in the parks.

For both MS, the parks with the assigned tree AMR of 1% provided longer ecosystem service benefits than those with the assigned tree AMR of 3%. Under the 1% AMR, the tree rotation periods after 2020 varied among the 25 parks, i.e., 22–45 years for MS1 and 29–50 years for MS2. Interestingly, the tree communities in some parks might not reach maturity in 2071 (the 50^{th} year) because their maximum $C_{seq\text{-}den}$ were detected this year and tended to increase beyond the forecasted period (Table 3). Under the 3% AMR, the tree rotation periods in the parks were shorter, i.e., 14–28 years for MS1 and 14–30 years for MS2 (Table 3). On average, the tree rotations in the 25 parks should be conducted after 2057 (37 years after 2020) and 2065 (45 years after 2020) under MS1 and MS2, respectively, for low tree AMR ($\leq$1%). They should be done no later than 2041 (21 years after 2020) and 2043 (23 years after 2020) under MS1 and MS2, respectively, for higher tree AMR (Table 3).

In this study, although i-Tree Eco was successfully applied to estimate the three park ecosystem services, its forecasting performance relied on both the quality and quantity of the local input data. Therefore, data on study locations and relevant variables should be sufficiently available for developing an i-Tree Eco model and reducing the uses of the software's default values for unobserved modeling variables [8,26–30,34]. Additionally, this software is not standalone but requires local data to be stored in its online database prior to simulating an i-Tree Eco model. The i-Tree Eco software was developed for use in the United States and expanded to Canada, Australia, Mexico, South Korea, Colombia, and most European countries; thus most of the necessary data in these countries are available in the software database [24]. For other countries (e.g., Thailand), researchers must submit local data for their study areas to the i-Tree database system and wait for the software team to validate them. These processes are time-consuming before the submitted data are incorporated into the online i-Tree database for running the i-Tree Eco models in the study areas.

3.3. Parks' benefit and management cost

The urban parks provide multiple ecosystem services as nature-based solutions; however, most of their ecosystem services were not evaluated in terms of monetary value in this study, e.g., recreation, aesthetics, and urban biodiversity. Thus, the annual estimated monetary value of the three ecosystem services of each park did not reflect the entire benefit of the park, and it could not be compared to the entire annual management cost of that park (e.g., in terms of cost–benefit ratio). For MC2 with the assigned tree AMR of 1%, the cumulative monetary value of the three ecosystem services of the 25 parks over the 50-year forecast was 27.7 million USD, or 0.55 million USD annually on average, and 150% higher than the estimated value in 2020 (i.e., 0.22 million USD, Table 2).

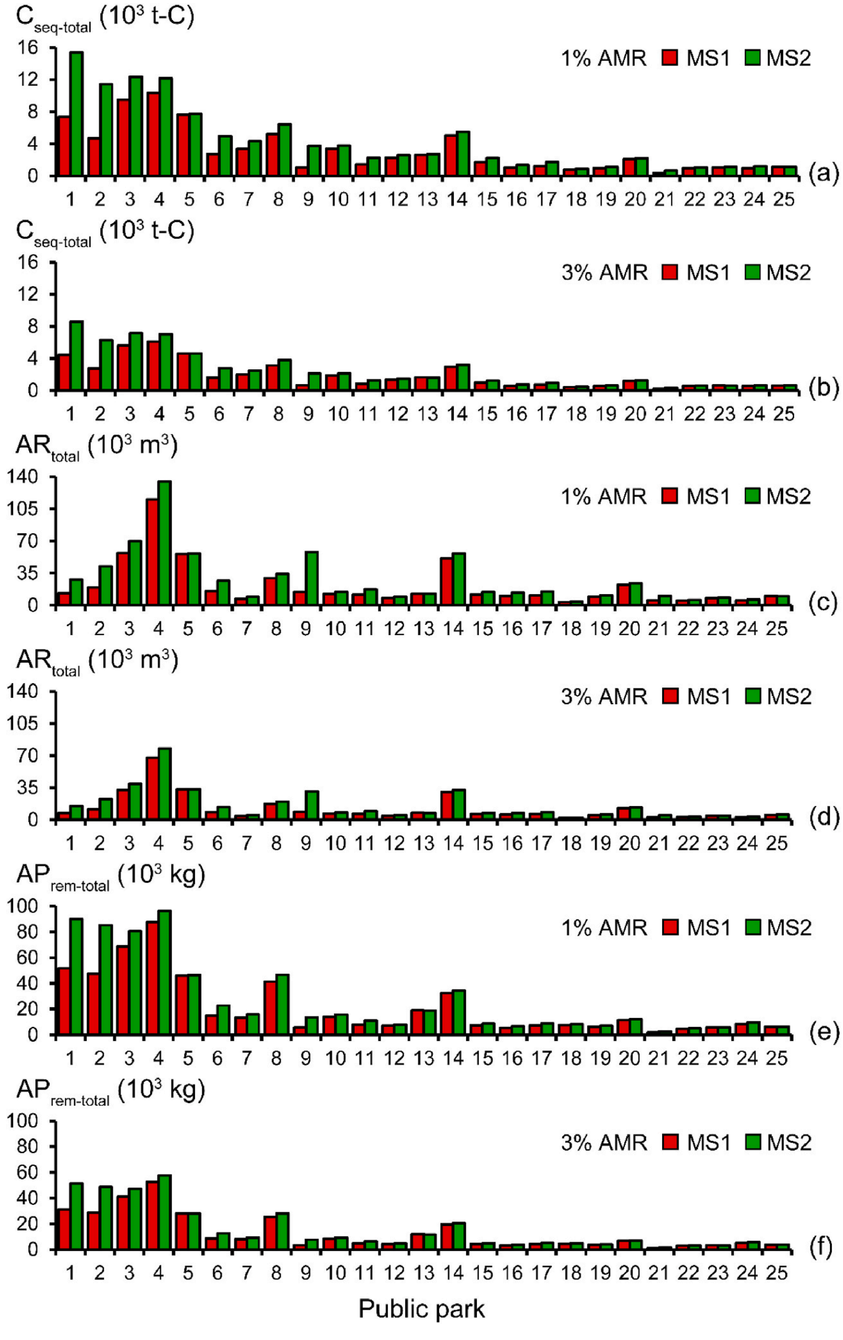

Fig. 3. The total amounts of carbon sequestration ($C_{seq\text{-}total}$), avoided runoff (AR_{total}), and air pollutant removal ($AP_{rem\text{-}total}$) in Parks 1–25 for the 50 forecasted years (2021–2071) obtained from modeling scenarios (MS) 1 (no greening improvement) and 2 (greening improvement) with the assigned tree annual mortality rates (AMR) of 1 and 3% for each MS.

The total management cost of the 25 parks in 2022 was 13.1 million USD, and most of this was for personnel (50.7%) and administrative (24.2%) tasks (Table 4, BMA, unpublished data). The remaining expenditure (25.1%) was for tree-related stewardship/maintenance (pest control, water, electricity, and cleanup), but there was no cost for planting, pruning, and removal of trees this year. The top three parks with the highest annual management cost (>one million USD) were Parks 2, 4, and 5 due to their large sizes and multiple functions to serve people, e.g., varieties in recreation spaces and plant collections and relevant exhibitions at Park 2; diverse spaces and equipment provided for both outdoor and indoor activities of urban dwellers at Park 4; and high density and diversity of trees to be maintained at Park 5. Unlike other parks, Park 1 had the lowest management cost (only for water and electricity utilization) although its size was the largest (107.9 ha). This was because the park area was mainly covered by three man-made lakes for water

Table 3
Tree rotation periods after 2020 in each of the 25 public parks obtained from two modeling scenarios (MS1: no greening improvement and MS2: greening improvement) over the 50-year forecast (2021–2071) with the assigned tree annual mortality rates (AMR) of 1 and 3% for each MS.

Park code	Tree rotation years after 2020			
	1% AMR		3% AMR	
	MS1	MS2	MS1	MS2
1	24	48	22	24
2	45	50	21	29
3	40	41	19	23
4	40	48	16	24
5	38	36	18	18
6	24	29	24	24
7	44	49	15	22
8	30	47	16	18
9	22	na	16	27
10	na	na	27	29
11	36	49	18	22
12	42	47	21	22
13	43	45	16	14
14	42	42	22	23
15	31	40	26	30
16	40	48	20	22
17	33	na	17	23
18	38	42	21	25
19	38	46	22	28
20	na	na	27	27
21	41	50	28	27
22	42	42	21	15
23	na	na	28	27
24	38	50	18	15
25	na	na	14	18
Minimum	22	29	14	14
Mean	37	45	21	23
Maximum	45	50	28	30

na = not available because the maximum density of carbon sequestration at a certain year that was used to indicate the tree maturity for rotation afterward in that park was detected at the 50th forecasted year and tended to increase beyond the forecasted period.

Table 4
The annual cost of the 25 public parks in 2022 (BMA, unpublished data).

Park code	Pest control	Water	Electricity	Repair	Cleanup & maintenance	Personnel	Administration	Total[a] (USD)
1	0.0	1049.5	675.4	0.0	0.0	0.0	0.0	1724.9
2	0.0	109,356.7	145,498.4	14,113.1	0.0	2,266,079.5	432,041.3	2,967,089.1
3	0.0	19,086.0	25,941.2	13,848.9	620,581.6	33,044.0	216,020.7	928,522.4
4	2871.1	19,453.8	76,935.9	28,356.0	14,229.1	821,483.4	360,034.5	1,323,363.8
5	0.0	3764.9	17,885.9	68,331.9	0.0	947,389.5	86,408.3	1,123,780.5
6	28,710.9	6436.0	19,248.6	0.0	95,774.7	568,961.6	194,418.6	913,550.4
7	0.0	2925.0	3871.9	0.0	0.0	317,073.9	144,013.8	467,884.6
8	0.0	5172.1	40,003.7	0.0	0.0	553,950.1	180,017.2	779,143.1
9	0.0	967.4	2813.4	0.0	111,886.3	0.0	144,013.8	259,680.9
10	0.0	1801.1	10,746.1	0.0	259,454.3	0.0	158,415.2	430,416.6
11	0.0	2172.9	9608.8	0.0	0.0	0.0	108,010.3	119,792.0
12	0.0	1148.1	5287.9	28,357.5	201,945.2	0.0	144,013.8	380,752.5
13	0.0	3437.1	21,908.4	133,795.6	0.0	334,210.2	115,211.0	608,562.3
14	0.0	6978.2	17,521.2	14,206.4	216,192.9	33,804.5	57,605.5	346,308.8
15	0.0	760.9	8029.3	27,558.1	109,046.0	35,888.9	86,408.3	267,691.5
16	0.0	3380.2	8484.7	0.0	111,886.3	34,890.6	100,809.6	259,451.5
17	0.0	3431.0	5971.9	0.0	0.0	283,275.1	64,806.2	357,484.1
18	0.0	1563.5	9461.3	53,976.5	95,774.7	26,938.8	100,809.6	288,524.4
19	0.0	4044.6	5737.5	14,243.5	0.0	14,243.5	57,605.5	95,874.5
20	0.0	5162.0	5625.5	61,383.9	0.0	0.0	115,211.0	187,382.4
21	0.0	292.5	4005.9	0.0	28,078.7	0.0	30,002.9	62,380.0
22	0.0	4191.8	16,451.3	0.0	0.0	173,632.8	72,006.9	266,282.8
23	0.0	10,983.3	10,768.7	28,265.9	0.0	138,867.4	64,806.2	253,691.4
24	0.0	4191.8	16,451.3	0.0	89,212.7	13,565.6	79,207.6	202,629.1
25	0.0	1137.8	18,153.8	0.0	93,194.1	46,743.3	57,605.5	216,834.6
Total	31,582.0	222,888.3	507,088.2	486,437.0	2,047,256.6	6,644,042.7	3,169,503.3	13,108,798.1
%	0.2	1.7	3.9	3.7	15.6	50.7	24.2	

[a] One USD = 34.83 Thai baht.

exercises, not green space. Additionally, Park 1 had no personnel and administration costs because its management-related tasks were performed by the same staff and workers hired for Park 2.

4. Conclusions

The i-Tree Eco software was successfully applied to estimate the parks' three ecosystem services (C_{seq}, AR, and AP_{rem}) in this study. The two MS (MS1: no greening improvement and MS2: greening improvement) with the assigned tree AMR of 1 and 3% for each MS were developed to forecast the three ecosystem services of the 25 parks over 50 years after 2020. The forecasts portrayed the variations in the ecosystem services of the urban parks as the results of the synergistic interactions of the different tree planting specifications and tree mortality rates. The greening improvement (MS2) with the assigned tree AMR of 1% could greatly maximize the parks' ecosystem services in the long term when the surviving trees in the parks were full-grown. The tree rotation period was another key variable to maintain the parks' optimal ecosystem services, and it was a site-specific variable that varied park by park in this study. Tree rotation should be carried out in a park when the planted trees pass maturity, and this could be identified as the time that the trees' C_{seq} density begins to decline. On average, the tree rotations in the 25 parks should be conducted after 2057 (37 years after 2020) and 2065 (45 years after 2020) under MS1 and MS2, respectively, for low tree AMR ($\leq$1%). They should be performed no later than 2041 (21 years after 2020) and 2043 (23 years after 2020) under MS1 and MS2, respectively, for higher tree AMR. The urban parks provide multiple ecosystem services as nature-based solutions; however, most of their ecosystem services were not evaluated in terms of monetary value in this study, e.g., recreation, aesthetics, and urban biodiversity. Thus, the annual estimated monetary value of the three ecosystem services of each park did not reflect the entire benefit of the park. Hence, additional important aspects of ecosystem services provided by the parks should be studied so that their cost-benefit ratio can be derived and used to support relevant decision-making for better park management.

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Financial interests

The author has no relevant financial interests to disclose.

Code availability

Not applicable.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Data availability statement

The list of the observed tree species in this study are available on the Online Resource 1.

CRediT authorship contribution statement

Nuanchan Singkran: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article (Online Resources 1 and 2) can be found online at https://doi.org/10.1016/j.heliyon.2023.e22002.

References

[1] P. Bolund, S. Hunhammar, Ecosystem services in urban areas, Ecol. Econ. 29 (1999) 293–301.
[2] L. Loures, L. Costa, The role of urban parks to enhance metropolitan sustainability: the case of Oporto, Int. J. Energy Environ. 6 (4) (2012) 453–461.
[3] J. Breuste, J. Schnellinger, S. Qureshi, A. Faggi, Urban ecosystem services on the local level: urban green spaces as providers, Ekol. Bratisl. 32 (2013) 290–304, https://doi.org/10.2478/eko-2013-0026.
[4] T. Mexia, J. Vieira, A. Príncipe, A. Anjos, P. Silva, N. Lopes, C. Freitas, M. Santos-Reis, O. Correia, C. Branquinho, P. Pinho, Ecosystem services: urban parks under a magnifying glass, Environ. Res. 160 (2018) 469–478, https://doi.org/10.1016/j.envres.2017.10.023.
[5] R. Ibrahima, A. Clayden, R. Cameron, Tropical urban parks in Kuala Lumpur, Malaysia: Challenging the attitudes of park management teams towards a more environmentally sustainable approach, Urban For. Urban Green. 49 (2020), 126605, https://doi.org/10.1016/j.ufug.2020.126605.
[6] D.V. Ciro, J.E.C. Barriga, I.C.H. Rincón, The removal of $PM_{2.5}$ by trees in tropical Andean metropolitan areas: an assessment of environmental change scenarios, Environ. Monit. Assess. 193 (7) (2021) 396, https://doi.org/10.1007/s10661-021-09171-2.
[7] N. Kabisch, R. Kraemer, M.E. Brenck, D. Haase, A. Lausch, M.L. Luttkus, T. Mueller, P. Remmler, P.v. Döhren, J. Voigtländer, J. Bumberger, A methodological framework for the assessment of regulating and recreational ecosystem services in urban parks under heat and drought conditions, Ecosyst. People 17 (2021) 464–475, https://doi.org/10.1080/26395916.2021.1958062.
[8] A. Yarnvudhi, N. Leksungnoen, P. Tor-Ngern, A. Premashthira, S. Thinkampheang, S. Hermhuk, Evaluation of regulating and provisioning services provided by a park designed to be resilient to climate change in Bangkok, Thailand, Sustainability 13 (2021), 13624, https://doi.org/10.3390/su132413624.
[9] A. Prigioniero, B. Paura, D. Zuzolo, M. Tartaglia, A. Postiglione, P. Scarano, S. Bellenger, A. Capuano, E. Serpe, R. Sciarrillo, C. Guarino, Holistic tool for ecosystem services and disservices assessment in the urban forests of the Real Bosco di Capodimonte, Naples, Sci. Rep. 12 (2022), 16413, https://doi.org/10.1038/s41598-022-20992-0.
[10] BMA, Bangkok Master Plan on Climate Change 2013–2023: Executive Summary Report (in Thai), Bangkok Metropolitan Administration, Bangkok, Thailand, 2015.. http://www.oic.go.th/FILEWEB/CABINFOCENTER9/DRAWER021/GENERAL/DATA0000/00000703.PDF.
[11] N. Singkran, Carbon sink capacity of public parks and carbon sequestration efficiency improvements in a dense urban landscape, Environ. Monit. Assess. 194 (2022) 750, https://doi.org/10.1007/s10661-022-10432-x.
[12] D.J. Nowak, E.J. Greenfield, R.E. Hoehn, E. Lapoint, Carbon storage and sequestration by trees in urban and community areas of the United States, Environ. Pollut. 178 (2013) 229–236, https://doi.org/10.1016/j.envpol.2013.03.019.
[13] E. Velasco, M. Roth, L. Norford, L.T. Molina, Does urban vegetation enhance carbon sequestration? Landsc. Urban Plan. 148 (2016) 99–107, https://doi.org/10.1016/j.landurbplan.2015.12.003.
[14] R. Othman, S. Suid, N.F. Mohd Noor, Z.M. Baharuddin, K.S.H.Y. Hashim, L.H. Lukman Hakim Mahamod, The influence of urban park green spaces, plant material specifications and spatial design organization and pattern towards carbon sequestration rate, Appl. Ecol. Environ. Res. 17 (4) (2019) 8079–8088, https://doi.org/10.15666/aeer/1704_80798088.
[15] Y. Wang, Q. Chang, X. Li, Promoting sustainable carbon sequestration of plants in urban greenspace by planting design: a case study in parks of Beijing, Urban For. Urban Green. 64 (2021), 127291, https://doi.org/10.1016/j.ufug.2021.127291.
[16] BMA, Major Public Parks in Bangkok (in Thai), The Environment Department and Strategy and Evaluation Department, Bangkok Metropolitan Administration, 2023, http://203.155.220.118/green-parks-admin/reports/report2.php. (Accessed 20 May 2023).
[17] A. Morani, D.J. Nowak, S. Hirabayashi, C. Calfapietra, How to select the best tree planting locations to enhance air pollution removal in the MillionTreesNYC initiative, Environ. Pollut. 159 (5) (2011) 1040–1047, https://doi.org/10.1016/j.envpol.2010.11.022.
[18] L.A. Roman, J.J. Battles, J.R. McBride, The balance of planting and mortality in a street tree population, Urban Ecosyst. 17 (2) (2013) 387–404, https://doi.org/10.1007/s11252-013-0320-5.
[19] A.K. Koeser, E.F. Gilman, M. Paz, C. Harchick, Factors influencing urban tree planting program growth and survival in Florida, United States, Urban for, Urban Green 13 (4) (2014) 655–661, https://doi.org/10.1016/j.ufug.2014.06.005.
[20] D.R. Hilbert, L.A. Roman, A.K. Koeser, J. Vogt, N.S.V. Doorn, Urban tree mortality: a literature review, Arboric. Urban For. 45 (2019) 167–200.
[21] DOPA. Number of Population (in Thai), Department of Provincial Administration (DOPA), 2023. https://stat.bora.dopa.go.th/new_stat/webPage/statByYear.php (Accessed 4 May 2023).
[22] BMA, Current Bangkok (in Thai), Strategy and Evaluation Department, Bangkok Metropolitan Administration, 2013. https://apps.bangkok.go.th/info/m.info/nowbma/. (Accessed 20 May 2023).
[23] Weather Spark, Climate and Average Weather Year Round in Bangkok, Cedar Lake Ventures, Inc., Thailand, 2023. https://weatherspark.com/y/113416/Average-Weather-in-Bangkok-Thailand-Year-Round. (Accessed 20 May 2023).
[24] i-Tree Cooperative, i-Tree Eco. i-Tree Software Suite Version 6.1.47, The Cooperative of the USDA Forest Service, Davey Tree Expert Co., National Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, and Casey Trees, 2006. https://www.itreetools.org/tools/i-tree-eco (Accessed 10 December 2022).
[25] i-Tree Cooperative, i-Tree Species. i-Tree Software Suite Version 6.1.47, The Cooperative of the USDA Forest Service, Davey Tree Expert Co., National Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, and Casey Trees, 2006. https://species.itreetools.org/. (Accessed 15 February 2023).
[26] C. Andrew, D. Slater, Why some UK homeowners reduce the size of their front garden trees and the consequences for urban forest benefits as assessed by i-Tree ECO, Arboric. J. 36 (2014) 197–215, https://doi.org/10.1080/03071375.2014.994388.
[27] M. Alonzoa, J.P. McFadden, D.J. Nowak, D.A. Roberts, Mapping urban forest structure and function using hyperspectralimagery and lidar data, Urban For. Urban Green. 17 (2016) 135–147, https://doi.org/10.1016/j.ufug.2016.04.003.

[28] M. Intasen, R.J. Hauer, L.P. Werner, E. Larsen, Urban forest assessment in Bangkok, Thailand, J. Sustain. For. 36 (2) (2017) 148–163, https://doi.org/10.1080/10549811.2016.1265455.
[29] V.M. Jayasooriya, A.W.M. Ng, S. Muthukumaran, B.J.C. Perera, Green infrastructure practices for improvement of urban air quality, Urban For. Urban Green. 21 (2017) 34–47, https://doi.org/10.1016/j.ufug.2016.11.007.
[30] G. Kim, P. Coseo, Urban park systems to support sustainability: the role of urban park systems in hot arid urban climates, Forests 9 (2018) 439, https://doi.org/10.3390/f9070439.
[31] R. Baraldi, C. Chieco, L. Neri, O. Facini, F. Rapparini, L. Morrone, A. Rotondi, G. Carriero, An integrated study on air mitigation potential of urban vegetation: from a multi-trait approach to modeling, Urban For. Urban Green. 41 (2019) 127–138, https://doi.org/10.1016/j.ufug.2019.03.020.
[32] V.A. Parsa, E. Salehi, A.R. Yavari, P.M.v. Bodegom, Analyzing temporal changes in urban forest structure and the effect on air quality improvement, Sustain. Cities Soc. 48 (2019), 101548, https://doi.org/10.1016/j.scs.2019.101548.
[33] P. Song, G. Kim, A. Mayer, R. He, G. Tian, Assessing the ecosystem services of various types of urban green spaces based on i-Tree Eco, Sustain. Times 12 (2020) 1630, 10.3390/su12041630.
[34] R. Moody, N. Geron, M. Healy, J. Rogan, D. Martin, Modeling the spatial distribution of the current and future ecosystem services of urban tree planting in Chicopee and Fall River, Massachusetts, Urban for, Urban Green 66 (2021), 127403, https://doi.org/10.1016/j.ufug.2021.127403.
[35] W. Rainey, M. McHale, M. Arabi, Characterization of co-benefits of green stormwater infrastructure across ecohydrologic regions in the United States, Urban for, Urban Green 70 (2022), 127514, https://doi.org/10.1016/j.ufug.2022.127514.
[36] S.M. Saunders, E. Dade, K.V. Niel, An Urban Forest Effects (UFORE) model study of the integrated effects of vegetation on local air pollution in the Western Suburbs of Perth, WA, in: F. Chan, D. Marinova, R.S. Anderssen (Eds.), 19th International Congress on Modelling and SimulationPerth, 2011, pp. 1824–1830. Australia, https://mssanz.org.au/modsim2011/E1/saunders.pdf.
[37] E.G. McPherson, P.J. Peper, Urban tree growth modeling, Arboric. Urban For. 38 (5) (2012) 172–180.
[38] S. Hirabayashi, Air Pollutant Removals, Biogenic Emissions and Hydrologic Estimates for i-Tree Applications, USDA Forest Service, Davey Tree Expert Company, 2016 and other cooperators, 2016. https://www.itreetools.org/documents/112/Air_Pollutant_Removals_Biogenic_Emissions_and_Hydrologic_Estimates_for_iTree_v6_Applications.pdf. (Accessed 7 May 2023).
[39] S. Hirabayashi, T.A. Endreny, Surface and Upper Weather Pre-processor for i-Tree Eco and Hydro, USDA Forest Service, Davey Tree Expert Company, 2016 and other cooperators, 2016, in: https://www.itreetools.org/documents/52/Surface_weather_and_upper_air_preprocessor_description.pdf. (Accessed 7 May 2023).
[40] D.J. Nowak, Understanding i-Tree: 2021 Summary of Programs and Methods, Forest Service, U.S. Department of Agriculture (USDA), Madison, WI, 2021.
[41] B. Thaiutsa, L. Puangchit, R. Kjelgren, W. Arunpraparut, Urban green space, street tree and heritage large tree assessment in Bangkok, Thailand, Urban for, Urban Green 7 (2008) 219–229, https://doi.org/10.1016/j.ufug.2008.03.002.
[42] P. Thaweepworadej, K.L. Evans, Species richness and ecosystem services of tree assemblages along an urbanisation gradient in a tropical mega-city: consequences for urban design, Urban For. Urban Green. 70 (2022), 127527, https://doi.org/10.1016/j.ufug.2022.127527.
[43] C.Y. Jim, W.Y. Chen, Assessing the ecosystem service of air pollutant removal by urban trees in Guangzhou (China), J. Environ. Manage. 88 (4) (2008) 665–676,. doi:10.1016/j.jenvman.2007.03.035.
[44] N. Leksungnoen, W. Eiadthong, R. Kjelgren, Thailand's catastrophic flood: Bangkok tree mortality as a function of taxa, habitat, and tree size, Urban For. Urban Green. 22 (2017) 111–119, https://doi.org/10.1016/j.ufug.2017.01.016.