Evaluation of condition and ecosystem services of street trees in Kyoto City urban area

京都市街地における街路樹の現状及び生態系サービスの評価に関する研究

Xiaoyang Tan

Landscape Ecology and Planning
Graduate School of Global Environmental Studies
Kyoto University

2022

ABSTRACT

Street trees are integral components of urban green infrastructure, contributing significantly to local amenities through a wide range of environmental, social, and economic benefits. As the urban densification process and infill development, the attendant problems of limitations on available growing space, present a stressful environment for street trees survival, healthy growth, and longevity. In addition, many local governments fail to recognize the importance of street trees due to unknown economic values. Consequently, pressures on municipal budgets drive management decisions aimed at reducing tree expenditures. This situation can be extremely urgent in highly developed urban areas in countries like Japan. To establish long-term plans for managing the trees in the urban region, a comprehensive assessment of street trees benefits is needed. This dissertation takes Kyoto City, the second ancient city in Japan, as the study site. The research aims to evaluate the status and ecosystem services of street trees in Kyoto City through the combination of field inventories, experimental analysis, geographic information, and computational models. The results revealed that the majority of 1230 sampled street trees in Kyoto City perform well. Tree health condition was significantly related to pruning intensity, tree pit size, adjacent land use, presence/absence of tree grate or guard, the width of sidewalk, tree height, presence/absence of dedicated cycle route, tree pit pattern, crown light exposure, DBH and tree pit type. *Platanus × acerifolia* and other trees with large diameters exhibited relatively poor condition, along with those in tree pits with concrete paving, without tree grates, or in industrial areas, whereas trees planted in strips exceeding 1.8 m in length and exposed to weak pruning showed the best condition. Regarding the below-ground part of the tree, our study provides evidence that soil hardness (50-60 layers) depth would be most strongly influence the tree attributes (*Ginkgo biloba Linn.*). Furthermore, our study presented that the 1230 sample trees deliver ecosystem service benefits at US$71,434.21 annually or US$58.07/tree/year. The annual value of each function was estimated at US$41.34/tree for carbon storage and sequestration, US$3.26/tree for stormwater runoff reduction, US$11.80/tree for adverse health mitigation effects, and US$1.67/tree for energy savings. The street tree species of Kyoto City that produce the highest average annual benefits are among the largest trees currently in the population, including *Platanus × yedoensis* (US$225.32/tree), *Zelkova serrata* (US$123.21/tree), *Salix babylonica* (US$80.10/tree), and *Platanus × acerifolia* (US$65.88/tree). Our research is based on the empirical data to demonstrate a comprehensive understanding of the current condition of street trees, ecosystem services for Kyoto City, and providing baseline information for decision-makers and managers to make effective urban trees species selection, management decisions, setting priorities.

ACKNOWLEDGEMENTS

First of all, I would like to express my thanks to the supervisory committee and the faculty members of Graduate School of Global Environmental Studies (GSGES). My deepest appreciation for my principal supervisor, Professor Shozo Shibata. His expertise, incredibly understanding, generous guidance and encourage me since my first year as a research student at Kyoto University. This research dissertation would not have been completed without his patience and persistent support on both an academic and a personal level. I would like to sincerely thank Associate Professor Katsue Fukamachi and Assistant Professor Ryo Nukina, who provided continuous support through professional and constructive assistance and valuable comments in each seminar. I am grateful to Special Assistant Professor Wen Liu for his constructive suggestions in statistical methods and share a lot of paper submission experience with me. To Professor Hiroaki Setoguchi, I sincerely thank him as the reviewer committee for his valuable suggestion and critical comment.

I am deeply indebted to Dr. Satoshi Hirabayashi from The Davey Tree Expert Company of USDA Forest Service, who greatly mentored and supported me in customizing and adjusting of i-Tree Eco model as well as publishing the article. His countless help and sharing insightful knowledge and experiences during our cooperation, not only allow me to expand the point of view about the research but also had the opportunity to get in touch with more motivated people in this research field.

Many thankful would like to be expressed to the people who provided kindly support and assistance in my field survey and research experiments. I would appreciate receiving much help from Assistant Professor Yui Oyake from Kagawa University for her kindly suggestions on my field data collection and research plan of soil part. Deeply appreciate Professor Shinya Funakawa and members from the Laboratory of Terrestrial Ecosystems Management and Professor Kenichiro Kosugi, Specific Assistant Professor Naoya Masaoka from the Laboratory of Erosion Control of Kyoto University for their careful guidance on the soil experiments and generously providing experimental sites and equipment. I acknowledge Yuki Kato from Ueyakato Landscape for his laborious assistance in soil data collection.

This research also cannot be done without the members of the Laboratory of Landscape Ecology and Planning and Laboratory of the Landscape Architecture of Kyoto University who assisted with my field surveys and measurements. Particularly, my close colleague Florence, Cici, Kang, Li, Rory, Gavin, Meimei, Anggi, Amin for their warm companionship and enlightenment.

Finally, I would like to extend my deep appreciation to my lovely family: my father and mother and all my dear relatives for their kind spiritual support and great patience at all times, especially in truly understanding me to explore and pursue my interests. Last but not the least, special thanks to the Japanese Government (MEXT) Scholarship, Kyoto City Construction Bureau, JSPS KAKENHI for their long-term support.

CONTENT

ABSTRACT .... **I**

ACKNOWLEDGEMENTS .... **II**

CONTENT .... **III**

LIST OF FIGURES .... **V**

LIST OF TABLES .... **VI**

LIST OF APPENDIXES .... **VII**

1. GENERAL INTRODUCTION **1**

1.1 BACKGROUND OF STUDY 1
1.1.1 Ecosystem services in urban area and their valuation 1
1.1.2 Street trees as providers of ecosystem services 4
1.1.3 The challenges of street trees 5
1.1.4 Street trees in Japan 7
1.2 THE LITERATURE REVIEW AND RESEARCH QUESTIONS 9
1.2.1 Previous studies 9
1.2.2 Main gap 12
1.3 THE PURPOSE OF STUDY 13
1.3.1 Study site 13
1.3.2 Main objectives of study 15
1.4 METHODOLOGICAL FRAMEWORK 15
1.4.1 Structure of study 15
1.4.2 Methodologies 16
1.5 REFERENCE 18

2. ABOVE-GROUND GROWING CONDITIONS AND LIMITATIONS FOR STREET TREE PERFORMANCE IN KYOTO CITY **25**

2.1. INTRODUCTION 25
2.2. MATERIALS AND METHODS 27
2.2.1. Study site 27
2.2.2. Street tree management in Kyoto City 27
2.2.3. Selection of sample trees 27
2.2.4. Data collection 28
2.2.5. Data analysis 29
2.3. RESULTS 34
2.3.1. Health condition of street trees 34
2.3.2. Determinants for tree health 35
2.4. DISCUSSION 36
2.5. CONCLUSION 39
2.6. REFERENCE 40

3. URBAN SOIL PROPERTIES AND LIMITATIONS FOR STREET TREE PERFORMANCE

IN KYOTO, CITY 44

3.1. INTRODUCTION 44
3.2. MATERIALS AND METHODS 46
3.2.1. Study site 46
3.2.2. Target species 46
3.2.3. Data collection 46
3.2.4. Soil data analysis 49
3.3. RESULTS AND DISCUSSION 50
3.3.1. Tree attributes 50
3.3.2. Soil properties 51
3.3.3. Soil hardness 53
3.3.4. Soil gas aeration 55
3.3.5. Soil properties correlation with tree attributes 55
3.3.6. Research limitation 57
3.4 CONCLUSION 57
3.5. REFERENCE 57

4. ESTIMATION OF ECOSYSTEM SERVICES PROVIDED BY STREET TREES IN KYOTO CITY 61

4.1. INTRODUCTION 61
4.2. MATERIALS AND METHODS 62
4.2.1. The City of Kyoto 62
4.2.2. Collecting tree data 63
4.2.3. Estimation of ecosystem services by i-Tree Eco 63
4.3. RESULTS 69
4.3.1. Species composition 69
4.3.2. Size distribution 69
4.3.3. Ecosystem services 70
4.4. DISCUSSION 75
4.4.1. Benefits-Cost Comparison 75
4.4.2. Advantages 76
4.4.3. Limitations and future directions 76
4.5. CONCLUSIONS 77
4.6. REFERENCES 78

5. GENERAL DISCUSSION & CONCLUSION 83

5.1. SUMMARIZATION OF THIS STUDY 83
5.2. PROPOSALS FOR MANAGEMENT AND PLAN OF STREET TREES IN KYOTO CITY 84
5.2.1. Street tree species selection 84
5.2.2. Street tree management and maintenance 84
5.3. FUTURE STUDIES 86
5.4. REFERENCE 86

APPENDIXES 87

LIST OF FIGURES

Figure 1. 1 Ecosystem Services and Their Links to Human Well-being (*source*: adapted from MEA 2005) 2
Figure 1. 2 The visualization of the benefits/ ecosystem services provided by urban trees in our city 5
Figure 1. 3 The demonstration of the vicious circle about the challenge of street trees 7
Figure 1. 4 The green corridors (緑の軸) area in Kyoto City (*source*: adopted the basic plan for 14
Figure 1. 5 The study area in Kyoto City (*source*: Author) 15
Figure 1. 6 The structure of this thesis 16
Figure 1. 7 The process flow chart of i-Tree eco model (*source*: Author) 17

Figure 2. 1 Study site in Kyoto City, Japan (*source*: Author) 28
Figure 2. 2 Proportion of different health condition classifications of 34
Figure 2. 3 Street tree examples in constrained planting space having potential conflict with 37
Figure 2. 4 Comparison of street tree health score (H) by tree pit size (m) for pruning level. 38

Figure 3. 1 Soil sampling protocol (A) and the research sites in Kyoto City (B). Sites: 1-Higashioji-Dori (HO); 2-Kawabata-Dori (KB); 3-Kawaramachi-Dori (KR); 4-Horikawa-Dori (HK); 5-Gojo-Dori (G) 47
Figure 3. 2 The SH Penetrometer Experiment and gas concentration measurement, (A) a cone penetrometer equipped with a 3kg weight to push the cone penetrating soils and datalogger was used to record each one drop penetrability (ODP cm/drop) (*source*: Daito Techno Green Co., Ltd); (B) Gas concentration sensor device (*source*: Author); (C) A gas sampling pipe connected with the gas sensor (*source*: Yuki Kato). 48
Figure 3. 3 The USDA soil classification with shaded area (red frame) encompassing the range of the textural classes in our studies. 52
Figure 3. 4 The pattern of 30 sample street trees soil hardness (total 60 sampling points, 2points/tree) in five streets of Kyoto City; Horizontal axis (S) represents the penetrating depth(cm) per one drop of the weight and vertical axis represents the cumulative depth (cm). 54

Figure 4. 1 Location of sample street trees in the urban area of Kyoto City. 63
Figure 4. 2 DBH size distribution of predominant street tree species compared to an "ideal" distribution (Richards, 1983). Note: The "Kyoto" classification represents the total of the sampled street trees 70

LIST OF TABLES

Table 1. 1 Methods to assess ecosystem services (*source:* extracted from Ranganathan et al., 2008) 2
Table 1. 2 The classification of important ecosystem services in urban areas (*source*: extracted from Gómez-Baggethun and Barton, 2013) 4
Table 1. 3 Environmental stresses influencing street trees (*source*: adapted from Dover, 2015) 6
Table 1. 4 Categories of factors associated with tree growing in urban area (*source*: design by Author and abstracted from Hilbert et al., 2019) 10

Table 2. 1 The description of street tree data collected by field survey in Kyoto City. 30
Table 2. 2 The descriptive statistics of seven common tree species data used in regression model. 32
Table 2. 3 Final models and regression results (only the variables that showed significant results are presented). 33
Table 2. 4 The health conditions of 1230 street trees by five categories in Kyoto City. 34

Table 3. 1 An example of soil hardness measurement data 50
Table 3. 2 The health conditions of 30 sampled trees of *G.biloba* by five categories 50
Table 3. 3 Statistical summary of selected soil properties of 90 streetscape soil samples 51
Table 3. 4 Evaluation criteria for soil analysis results for greening site, Research Committee of Japanese Institute of Landscape Architecture (2000) 52
Table 3. 5 Evaluation criteria for soil hardness by Hasegawa penetration meter, ...53
Table 3. 6 The average CO_2&O_2 (mol%) gas concentration of 26 valid sample trees 55
Table 3. 7 Pearson's correlation coefficients between the tree health and soil properties 56

Table 4. 1 Model input data and parameters used for i-Tree Eco run for Kyoto City 65
Table 4. 2 Predominant street tree species and their leaf area 69
Table 4. 3 Predominant street tree species and their annual carbon storage and sequestration values in Kyoto City. 70
Table 4. 4 Annual air quality and stormwater effects from sample street trees in Kyoto City. 71
Table 4. 5 Reference US counties for each metric and air pollutant assigned to Kyoto, Japan. 71
Table 4. 6 Annual reduction in adverse health effect incidences and associated monetary value ($) due to pollutant reduction from sample street trees in Kyoto City. 72
Table 4. 7 R-value and Q-value conversion results (post-1980 vintage for the southeast region). 72
Table 4. 8 Japanese house vintages assignment to the US's vintages. 73
Table 4. 9 Annual energy savings and monetary values provided by street trees in Kyoto City. 73
Table 4. 10 Annual benefits-cost summary of sample street trees. 74
Table 4. 11 Monetary value of predominant street tree species in Kyoto City. 74

LIST OF APPENDIXES

Appendix 1. The street tree species collected by field survey in Kyoto City 87
Appendix 2. Field survey sheet used for street trees inventory data collection in Kyoto city, Japan 88
Appendix 3. Tree decline rating assessment sheet used in Kyoto city, Japan.. 89
Appendix 4. Summary of the model for *Ginkgo biloba* 90
Appendix 5. Summary of the model for *Acer buergerianum* 90
Appendix 6. Summary of the model for *Zelkova serrata* 91
Appendix 7. Summary of the model for *Prunus*.spp 91
Appendix 8. Summary of the model for *Liriodendron tulipifera* 92
Appendix 9. Summary of the model for *Cornus florida*.. 92
Appendix 10. Summary of the model for *Platanus × acerifolia* 93
Appendix 11. Three pruning intensity classifications in Japan (*Gingko biloba* as an example)............. 94
Appendix 12. Two-stage pruning method in Kyoto, Japan (Matsumoto et al., 2019) 95
Appendix 13. Tree root system morphology of *Ginkgo biloba* Linn. (DBH: 30cm, Total height: 14m, tree age: 40 years, Maximum depth of root of 2.5m) (Karizumi, 1979) 96

1. General Introduction

1.1 Background of study

1.1.1 Ecosystem services in urban area and their valuation

Ecosystem services refer to the life-support functions performed by natural ecosystems that underpin humanity's most fundamental sources of well-being (Daily, 1997). Human populations directly or indirectly derive ecosystem goods and services from ecosystem functions (Costanza et al., 1997). Since the establishment of the Millennium Ecosystem Assessment (MEA, 2005) and the publication of The Economics of Ecosystems and Biodiversity (TEEB) (Kumar, 2012), ecosystem services have gained broader attention in many parts of the world at national, regional or local levels (Raum et al, 2019). Ecosystem services include provisioning services (e.g., water and food); regulating services (e.g., regulation of floods, drought, land degradation, and disease); and cultural service (e.g., recreational, spiritual, religious and other nonmaterial benefits), which directly affect people, and supporting services (e.g., soil formation, nutrient cycling) needed to maintain the other services (MEA, 2005) (Fig 1.1). The Millennium Ecosystem Assessment provides an integrated assessment of the consequences of change for human well-being and to analyzes options available to enhance the conservation of ecosystems and their contributions to meeting human needs (MEA, 2005). The information of assessing the condition and trends of the ecosystem services in location can offer a baseline that reveals how current trends affect ecosystem service's supply and associated risks and opportunities for the decision (Ranganathan et al., 2008). There is a variety of methods used by The Millennium Ecosystem Assessment to assess the condition and trends of ecosystem services for sub-global assessments include analysis of remotely sensed data, geographic information system, inventories, ecological models, participatory approaches, and expert opinions (see Table 1.1) (Ranganathan et al., 2008).

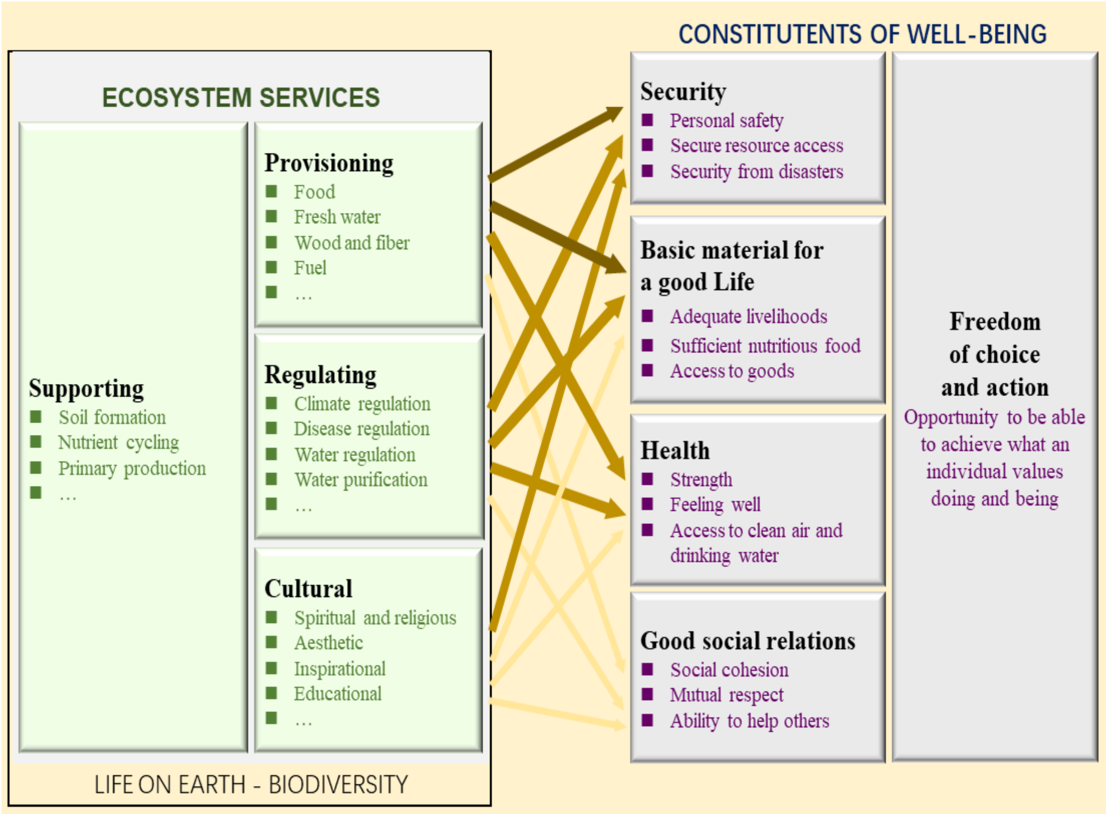


Figure 1. 1 Ecosystem Services and Their Links to Human Well-being (***source***: adapted from MEA 2005)

Table 1. 1 Methods to assess ecosystem services (***source:*** extracted from Ranganathan et al., 2008)

Method	***Description***	***Sample uses***
Remote Sensing	Data obtained from satellite sensors or aerial photographs (LANDSAT, MODIS)	Assessment of large areas, land cover/land use, biodiversity
Geographic Information Systems	Software that spatially maps and analyzes digitized data (ArcGIS, ArcView, IDRISI)	Analysis of temporal changes in ecosystems; overlaying social and economic information with ecosystem information; correlating trends in ecosystem services with land use change
Inventories	Lists	Tally ecosystem services and natural resources
Ecological Models	Simplified mathematical expressions that represent the complex interactions between physical, biological, and socioeconomic elements of ecosystem (SWAT, IMAGE, IMPACT, WaterGAP, ECOPath, Ecosim)	Filling gaps in existing data; quantifying the effects of management decisions on the condition of ecosystem services; projecting long-term effects of changes in ecosystem condition; assessing the effects of individual drivers and scenarios on ecosystem condition and the supply of ecosystem services; exploring the links between elements in a system
Participatory Approaches and Expert Opinion	Information supplied by stakeholder groups, scientific experts, workshops, traditional knowledge	Collection of knowledge not available in scientific literature; fills gaps in the literature; adds new perspectives, knowledge, and values to assessment

Globally, more than half of the world's population lives in urban areas, and by 2050, more than two-thirds of people are expected to reside in urban areas (UN, 2018). The urban area become a key nexus of the relationship between people and nature and are a crucial center of demand for ecosystem services and also generates huge environmental impacts (Elmqvist et al., 2015). Moreover, the increasing economic activities concentrated in cities, therefore present extreme challenges but also unprecedented to enhance the resilience and ecosystem functioning of cities (Elmqvist et al., 2015). Ecosystem services provided in urban areas contributed to the quality of urban life, e.g., microclimate, air quality, noise levels that cannot be improved with the help of distant ecosystems (Bolund and Hunhammar, 1999; Gómez-Baggethun and Barton, 2013).

Urban ecosystem services are generally characterized by a high intensity of demand/use due to a very large number of immediate local beneficiaries, compared for example to ecosystem services generated in rural areas (Elmqvist et al., 2015). The range of 'urban ecosystem service', defined as those provided by urban ecosystems and their components (Gómez-Baggethun and Barton, 2013). For simplicity, urban ecosystem, that is, all the urban 'green and blue infrastructure' (Bolund and Hunhammar, 1999; Elmqvist et al., 2015), including green spaces, such as parks, urban forests, cemeteries, vacant lots, gardens and yards, campus areas, Landfills; and blue spaces, including streams, lakes, ponds, artificial swales, and storm water retention ponds (Gómez-Baggethun and Barton, 2013; Elmqvist et al., 2015). More specifically, seven different urban ecosystems were identified, they are, street trees, lawns/parks, urban forests, cultivated land, wetlands, lake/sea, and streams (Bolund and Hunhammar, 1999). Gómez-Baggethun and Barton, (2013) proposed a classification of ecosystem functions and services in urban areas based on the literature review was extracted in Table 1.2.

In the recent decade, ecosystem services provided in urban areas have been received increasing attention as part of the policy debate on green infrastructure. Conserving and restoring green infrastructure and ecosystem-based adaptation to climate change are gaining interest, particularly since such investments simultaneously reduce the ecological footprints and the ecological debt of cities while enhancing resilience, health, and quality of life for their inhabitants (Gómez-Baggethun and Barton, 2013; Elmqvist et al., 2015). Understanding the importance of protecting, restoring, and enhancing green infrastructure and ecosystem services in cities is not only ecologically and socially desirable, but also contributes to a more economically viable, resource-efficient city structure and design, which is essential to include in decision-making processes. Additionally, such information can help to guide urban and landscape planners, architects, restoration practitioners, and public policymakers, as well as private and institutional stakeholders (Elmqvist et al., 2015).

Table 1. 2 The classification of important ecosystem services in urban areas (***source***: extracted from Gómez-Baggethun and Barton, 2013)

Functions and components	***Ecosystem service***	***Examples***
Energy conversion into edible plants through photosynthesis	Food supply	Vegetables produced by urban allotments and peri-urban areas
Percolation and regulation of runoff and river discharge	Water flow regulation and runoff mitigation	Soil and vegetation percolate water during heavy and/or prolonged precipitation events
Photosynthesis, shading, and evapotranspiration	Urban temperature regulation	Trees and other urban vegetation provide shade, create humidity and block wind
Absorption of sound waves by vegetation and water	Noise reduction	Absorption of sound waves by vegetation barriers, especially thick vegetation
Filtering and fixation of gases and particulate matter	Air purification	Removal and fixation of pollutants by urban vegetation in leaves, stems and root
Physical barrier and absorption on kinetic energy	Moderation of environmental extremes	Storm, floods, and wave buffering by vegetation barriers; heat absorption during severe heat waves
Removal or break down of xenic nutrients	Waste treatment	Effluent filtering and nutrient fixation by urban wetlands
Carbon sequestration and fixation in photosynthesis	Climate regulation	Carbon sequestration and storage by the biomass of urban shrubs and trees
Movement of floral gametes by biota	Pollination and seed dispersal	Urban ecosystems provide habitat for birds, insects, and pollinators
Ecosystems with recreational and educational values	Recreation and cognitive development	Urban parks provide multiple opportunities for recreation, meditation, and pedagogy
Habitat provision for animal species	Animal sighting	Urban green space provide habitat for birds and other animals people like watching

1.1.2 Street trees as providers of ecosystem services

Urban forests - trees canopy in cities, towns, and urbanized landscape, have been widely reported to provide valuable ecosystem services (Roman et al., 2014a). With the public recognition of the great value of urban forests and green infrastructure (especially trees), urban tree planting initiatives have been actively promoted as an urban planning strategy to reduce the environmental degradation caused by urbanization, ameliorate the climate change, improve the human well-being and enhance urban sustainability (Salmond et al., 2016). For instance, New York City launched the 'Million Trees' program to achieve the goal of ambitious tree canopy covers, and Melbourne City's 40% tree canopy cover target (Million Trees NYC, 2015; City of Melbourne, 2021).

Street trees, as a single entity, perhaps embody multiple functions than any other aspect of urban green infrastructure (Dover, 2015). As one of the most obvious features of urban greening, street trees have probably been part of the urban fabric as seen in several alleés and boulevards since the beginning of urbanization; records exist from the 16th century (Forrest and Konijnendilk, 2005). In addition to the most obvious effect of enhancing the aesthetics of streetscapes, the ecological benefits provided by street trees contribute significantly to local environmental, social, and

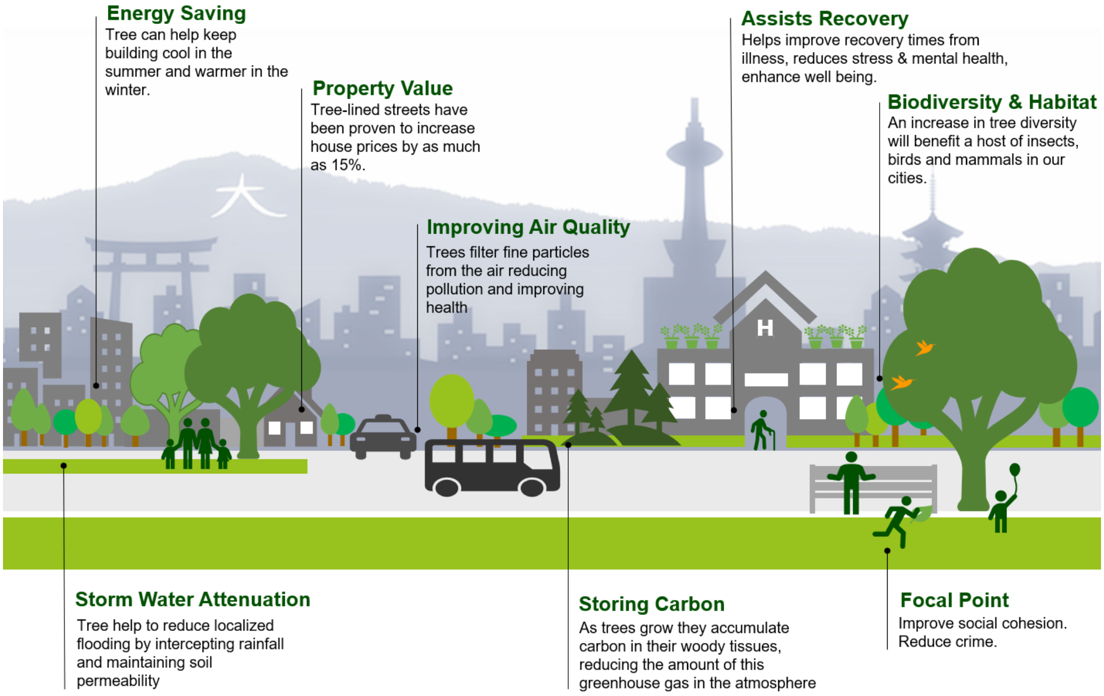


Figure 1. 2 The visualization of the benefits/ ecosystem services provided by urban trees in Kyoto City (***source***: design by Author and reference to Rogers et al.,2015)

economic aspects, including energy-saving, storm water management increases in property values, air quality improvement, carbon storage and sequestration, human physical health improvements, increasing biodiversity and habitats, and improving social cohesion (see Fig 1.2) (Maco and McPherson, 2003; Nowak et al., 2006; Roy et al., 2012; Mullaney et al., 2015).

1.1.3 The challenges of street trees

Continued urbanization worldwide and associated urban densification could influence the provision of urban greening space and comprehensive ecosystem services (Haaland and Konijnendijk van Den Bosch 2015; Jim et al., 2018). Dense urban area with the juxtaposition of buildings and roads and limited interstitial space poses major challenges to vegetation and urban greening, including lack of growing space; poor soil quality; pollutants; and conflicts with human activities (Jim et al., 2018). Street trees, as one of the existing greening assets in the urban street environment, were inherently threatened by multiple stresses from biophysical and anthropogenic factors. such as cramped above-ground environment, intrusions of structures into tree growth space, poor air quality, vandalism and inadvertent damages (Sæbø et al., 2003; Jim, 2004; Dover, 2015; Scharenbroch et al 2017; Hilbert et al., 2019) (Table 1.3). Due to the site conditions found in urban areas can often be more challenging than those found in natural forest areas, street trees are known to have lower mean life expectancy and higher mortality rates than the same species grown in non-urban areas (Moll, 1989; Roman and Scatena, 2011; Mullaney et al., 2015).

Table 1. 3 Environmental stresses influencing street trees (***source***: adapted from Dover, 2015)

Stress factor	***Major effect***
Climate	If the tree is not adapted to the planting site's climate, it may be susceptible to frost damage (either in the spring due to earlier budburst than local trees, or in the autumn if leaf fall is not early enough to harden the trees). May results in greater susceptibility to disease.
Water stress	In high temperatures trees need lots of water; this may not be available due to constricted root space and the sealed surface preventing rain penetration to roots. Urban centers are warmer than the countryside.
Oxygen starvation	In some circumstances, e.g., with highly compacted ground, waterlogging.
Light	Trees that are not shade adapted may suffer from low photosynthetic activity in narrow street; the effects are exacerbated when combined with high temperatures and thus high transpiration. Streetlights may cause delayed leaf fall/ winter hardening leading to frost damage.
Soil	Soil conditions need to be appropriate for the species/cultivar and should be determined before planting and soil modified or a different species used if necessary.
Air pollution	Trees are susceptible to damage by a range of pollutants, e.g., particulates, reducing photosynthesis, gaseous pollutants taken in via stomata, direct tissue damage. Some species are more tolerant than other.
Heavy pruning	Heavy pruning of trees to limit crown spread can leave trees open disease attack; heavy management can lead to decline of mature specimens leading to premature felling and replacement.

The establishment period- the first few years after tree planting- is generally viewed as the life stage with the highest mortality for street trees (Nowak et al., 1990; Koeser et al. 2014; Roman et al., 2014b, Roman et al., 2015). For instance, A previous meta-analysis research of street trees survival (Roman and Scatena, 2011) found typical annual mortality to be 3.5 to 5.1%; and Nowak et al., (2004) observed 6.6% annual mortality across all land use in Baltimore, MD. Tree survival is a performance metric for the long-term provision of ecosystem services from urban forestry initiatives. Therefore, an understanding of the factors that influence tree mortality can help managers target resources and enhance survival (Hilbert et al., 2019).

Despite the important concept "ecosystem services" has revealed the prominence of the myriad benefits of street trees, policy and decision-makers fail to recognize the importance of street trees due to unknown economic values, while the costs of damage by trees such as leaf litter and infrastructure damage are widely reported (Moore, 2009; Mullaney et al., 2015). Unlike conventional forestry and fruit trees, the economic benefits associated with urban trees cannot be easily quantified as they usually do not have a market value (McPherson, 2007). The perspective on the status of street trees cannot be raised as a major urban infrastructure asset without assigning the proper monetary value to those services which can be easily understood by policy and decision-makers and help turn appreciation into action (McPherson, 2007; Moore,2009; Leff, 2016).

In addition, municipal budget constraints are often a major obstacle to sustainable urban greening management (Leff, 2016). Without investment in tree management, the health and functionality of trees deteriorate. At present, the extensive urban green plans are viewed more as liabilities than assets due to the lack of money (Nilsson et al., 2007; McPherson, 2007). The research

Figure 1. 3 The demonstration of the vicious circle about the challenge of street trees (***source***: design by Author)

conducted in Petersburg, Russia (Nilsson et al., 2007) noted that the municipal budget for green-space establishment and management is only 10–20%, and the number of green areas is decreasing rapidly due to lack of funding.

As a result, pressures on municipal budgets drive management decisions aimed at reducing tree expenditures; The shrinking tree expenditures cannot provide good maintenance for trees, which exacerbates the threat to the street tree growth; the poor tree condition cannot support the long-term convey of ecosystem services (Fig 1.3)

1.1.4 Street trees in Japan

The history of street tree in Japan

The history of roadside trees in Japan can be traced back to around the 3rd Century (AD), and it is recorded that camphor trees were planted along the country roads in Japan for the first time (Cheng et al., 1999; Seko, 2017). The first record of country road tree planting as a government policy was in 759 AD. Willow (*Salix* sp.), cherry (*Prunus* sp.), and Japanese pagoda tree (*Sophora japonica* L.) were planted along the streets of Kyoto in the 9th Century (AD) (Cheng et al., 1999). The origin of modern street trees in Japan can be traced back to the Meiji era. The first planting of street trees in Japan was said to be in 1867 on the carriageway (Bashamichi) in Yokohama. The Edo shogunate has received pressure from the Western powers to open the ports and set up foreign settlements. Japanese merchants on both sides of the road rushed to plant willows and pine trees (Fujii, 2019). In 1873, the street trees of cherry and pine trees in Tokyo appeared at the sidewalks of the Ginza-Dori, which is introduced and influenced by European culture during the Meiji Era (Cheng et al., 1999; Fujii, 2019). The Road law enacted in 1960, street trees were positioned as appurtenances of the street (Ministry of Land, Infrastructure, Transport and Tourism, 1960).

The change of tree species selection in Japan

The Ministry of Land, Infrastructure, Transport, and Tourism is promoting the development of roadside greening to improve traffic comfort and create a better living environment in Japan. Street trees as an important road greening that can greatly exert various functions such as landscape improvement, environmental conservation, greenery formation, traffic safety, disaster prevention have been planted in large numbers along with the rapid urban development after the war (Iizuka and Funakubo, 2019). During the late 60s, the role of street trees was the focus of high survival and rapid growth to address the environmental issue for cities, such as the reduction of air pollutions and traffic noise. The tree species of the first stage mostly used the ginkgo (*Ginkgo biloba* Linn.), oriental plane tree (*Platanus × acerifolia*). In the 1970s, the concept of street trees planting changed from planting individual trees to planting in groups, usually in belts or mixed with shrubs and flowers (Cheng et al., 1999). The species selection of the second stage shifted to low maintenance cost and functional tree form, such as camphor tree, Japanese zelkova. The third stage has represented a trend to species of aesthetic value, such as those with flowers and autumn foliages (e.g., *Prunus yedoensis*, flowering dogwood (*Cornus florida* L.)) (Cheng et al., 1999).

The environmental condition for street trees in Japan

According to the Government Order on Road Design Standards (Ministry of Land, Infrastructure, Transport and Tourism, 1970), the standard width for the tree planting zone is 1.5m, which zone, which includes the curbs. However, the actual width of the planting base is usually less than 1.5m. Moreover, roadside planting space is often the first area to be sacrificed for complex underground infrastructure developments (e.g., installing gas pipes, cables, sewers), creating separated, narrow tree pits instead of continuous planting strips (Hamano, 2009; Iizuka, 2009).

In addition, the abundance of above-ground utility poles and overhead power grids present in most parts of Japan, which restricts the space for sidewalks, resulting in the need for periodic heavy pruning of street trees. In many instances, due to the shrinking tree maintenance expenditure, inappropriate heavy pruning was implemented instead of regular and periodically pruning, which can deteriorate the tree shape and growth (Nomura, 2009).

The street tree population in Japan

Until March 31, 2017, the number of street trees nationwide was about 6.7 million. By prefecture, Hokkaido, which has a long road extension, had the largest number, followed by metropolitan areas such as Tokyo, Aichi, and Osaka. Ginkgo (*Ginkgo biloba* Linn.) was the most common street tree species in Japan, followed by plum/cherry (*Prunus* spp.), Japanese zelkova (*Zelkova serrata* (Thunb.) Makino.), flowering dogwood (*Cornus florida* L.), trident maple (*Acer buergerianum*). The number of street trees has increased by 1.07 million from 1987 to 1992; increased 1.43 million by 1997, and increased 580,000 by 2002. While decreased 120,000 in the five years since 2007. Increased 80,000 trees by 2012, and decreased again 50,000 trees by 2017 (Iizuka and Funakubo, 2017).

In terms of changes in tree species, Ginkgo (*Ginkgo biloba* Linn.), cherry (*Prunus* spp.), and Japanese zelkova (*Zelkova serrata* (Thunb.) Makino.) remained in the top three since 1992. The ranking has been changing from 4^{th} place. As a feature of changes in recent years, the number of plane trees (*Platanus × acerifolia*) dropped from 3rd in 1987 to 10th in 2012, and the population is further decreasing and dropped to 12th until 2017(Iizuka and Funakubo, 2017). In addition, the number of flowering dogwood (*Cornus florida* L.) has increased remarkably, and it was ranked 7th in 1997 and become the 4th since 2002. It is considered that the reason for the increase or decrease of these tree species is that the number of plane trees (*Platanus* × *acerifolia*) has been reduced. Because it is generally difficult to manage due to the rapid growth and required for frequently pruning, as well as the characteristic of being vulnerable to decay. On the contrary, the selection of flowering dogwood (*Cornus florida* L.) is increasing, not only because of the beauty of flowers and autumn leaves but also for the constrained urban areas the height of the trees is easy to manage (Iizuka and Funakubo, 2019).

1.2 The Literature Review and Research Questions

1.2.1 Previous studies

Over the past decade, the primary purpose of street trees has changed from an aesthetic role of beautification and ornamentation to one that also includes the provision of ecosystem services and improves urban livability (Mullaney., 2015). The urban street environment, however, is beset with constraints and stresses to tree growth and longevity (Dover, 2015; Mullaney., 2015). A large proportion of the literature available for review described and discussed the challenges of growing street trees in urban environments, the ecological benefits of street trees and the assessment associated with ecosystem services.

The challenges of street trees growing in urban environments

The success of tree survival is essential to achieve the intended provision of ecosystem services. Continuing research on factors that influence tree survival provides insight into street trees tend to have lower mean life expectancy and higher mortality rates than the same species grown in non-urban areas (Moll, 1989; Roman and Scatena, 2011; Mullaney et al., 2015). To date, street trees research has identified various biophysical and human-related factors that affect street tree conditions. Biophysical factors include the types of tree species, tree size, and age, which are all closely related to the diameter at breast height (DBH) and soil condition (e.g., Iakovoglou et al., 2001; Nowak et al., 2004; Lu et al., 2010; Koeser et al., 2013). Known human-related factors include associations with surrounding land use, construction and development (e.g., street setting), vandalism, and stewardship or maintenance activities (e.g., Hauer,1994; Nowak et al., 2004; Lu et al., 2010; Ko et al., 2015; Limoges and Apparicio, 2018). Many studies have also suggested that a constrained growing condition is one of the most critical factors negatively affecting the growth of urban trees (Sæbø et al., 2003; Sanders and Grabosky, 2014, Dover, 2015; Mullaney et al., 2015). North et al. (2017) compared the tree growth, calculated as basal area increment, pre-and post-sidewalk construction, and found street trees planting in areas with a width of less than 1.25 m showed no growth recovery after 5 years of sidewalk construction activities, while larger tree pits positively correlated with better tree condition (Lu et al., 2010; Koeser et al., 2013). Research also acknowledged that human-related and biophysical factors will be deeply coupled, such as, species and site selection choices by tree professionals and residents related to later susceptibility to drought, irrigation may help trees to survive in some areas with varying precipitation (Roman et al., 2014a; Koeser et al.,2014; Mincey et al., 2013; Martin et al., 2016).

In addition, part of the problem from the complexity of underground infrastructure (sewer, electricity, gas, cable) and the limitations of these places on available space for tree roots can be attributed to poor tree performance (Jim, 1998). A lack of adequate volume of fertile soil and narrow rooting space is often one of the greatest challenges for street trees' long-term access to water and nutrients (Lindsey & Bassuk, 1992; Grabosky & Bassuk, 1995; Grabosky et al., 1998). Nowak (1994) suggested that street tree root growth and ultimate tree size are related to available soil volume. The previous studies of the soil profile in relation to urban tree performance (e.g., establishment, growth, longevity) yields much evidence that showing soil physical and chemical analytic methodology as an important tool to examine soils for their suitability for urban trees (Konijnendijk et al., 2005; Hawver and Bassuk, 2007; Scharenbroch and Catania, 2012). The importance of soil physical properties to tree condition is represented by the many works of literature shown the soil texture and bulk density large effect on the growth of trees (e.g., Jim, 1998; Harris, 2004; Scharenbroch and Catania, 2012; Kim and Yoo, 2021). For example, texture affects not only soil's structure but also water relation, aeration and soil compaction (Konijnendijk et al., 2005; Hawver and Bassuk, 2007). Soil chemical properties, especially the indicators of pH and nutrients influence tree growth (Jim,1998; Schoenholtz et al.,2000; Udawatta and Henderson 2003; Kim and Yoo, 2021).

Table 1. 4 Categories of factors associated with tree growing in urban area (***source***: design by Author and abstracted from Hilbert et al., 2019)

Factors	***Citations***
Biophysical factors	
Taxa (e.g., genus, species, cultivar)	Iakovoglou 2001; Nowak 2004; Lu et al 2010; Koeser et al. 2013; Koeser et al. 2014; Roman et al. 2015; Ko et al. 2015; Martin 2016; North 2017; Limoges 2018; etc.
Size/age	Nowak et al. 2004; Koeser et al. 2013; Roman et al. 2014(a); Roman et al. 2014(b); Ko et al. 2015; Martin 2016; North 2017; etc.
Site characteristics (e.g., planting space, site type, tree density)	Jim 2005; Lu et al. 2010; Koeser et al. 2013; Roman et al. 2014(a); Roman et al. 2014(b); Ko et al. 2015; Roman et al. 2015; etc.
Human-related factors	
Stewardship, maintenance, vandalism	Gilbertson and Bradshaw 1985; Lu et al. 2010; Yang et al. 2012; Koeser et al. 2014; Roman et al. 2014a; Ko et al. 2015; Roman et al. 2015; etc.
Land use	Nowak et al. 1990; Iakovoglou 2001; Nowak et al. 2004; Jim 2005; Ichikawa 2007; Lu et al. 2010; etc.
Construction and redevelopment activity	Hauer 1994; Koeser et al. 2013; North 2017; etc.
Infrastructure conflicts (e.g., overhead utilities, sidewalks, transportation)	Nowak et al. 1990; Nowak et al. 2004; Lu et al. 2010; van Doorn and McPherson 2018; etc.
Soil factors	
Soil texture	Jim 1998; Scharenbroch and Catania 2012; etc.
Bulk density	Jim, 1998; Harris, 2004; Scharenbroch and Catania, 2012; Kim and Yoo, 2021; etc.
Chemical Properties	Cekstere and Osvalde 2013 etc.
Soil Reaction (pH)	Jim,1998; Schoenholtz et al.,2000; Udawatta and Henderson 2003; Scharenbroch and Catania 2012; Kim and Yoo 2021; etc.
Soil compaction/soil hardness	Day and Bassuk 1994; Kume and Hioki 2006; etc.

The ecosystem services and quantification of urban trees

By the 1980s, the notable ecologist Rowan Rowntree published a series of papers in urban ecology (Rowntree 1984, 1986) which set the conceptual stage for much of our urban forestry research (Harris, 2004). Over the past decade, there have been tremendous advances in the knowledge of the benefits of urban trees. The USDA Forest Service and the National Urban and Community Forestry Advisory Council (NUCFAC) made significant commitments of time, talent, and resources to address this broad issue (Harris, 2004). In contemporary urban forestry research, ecosystem services studies are widespread (Roy et al., 2012; Mullaney et al., 2015; Roman et al., 2021). Research has highlighted the ecosystem services provided by urban trees from environmental, social, and economic perspectives, including air quality improvement (e.g., Nowak, 1994; McPherson et al.,1997; Maco and McPherson, 2003; Nowak et al., 2006), carbon storage and sequestration (e.g., McPherson and Simpson,1999; Nowak and Crane, 2002; Liu and Li, 2012; Nowak et al., 2013), stormwater runoff management (e.g., McPherson et al., 1999, Xiao et al., 2000a; Xiao et al., 2000b; Livesley et al., 2014), energy conservation or microclimate regulation (e.g., McPherson and Rowntree, 1993; McPherson and Simpson, 2003; Tan et al., 2016), human physical health improvements (e.g., Nilsson et al., 2011; Ulmer et al., 2016) and increases in property values (e.g., Anderson and Cordell,1988; Donovan and Butry, 2010).

The landscape approach establishing the value of trees including the replacement cost method and the trunk formula method do not explicitly account for their ecological benefits (Harris, 2004). The method used in quantifying the amenity benefits of urban forests and trees include the contingent valuation method (CVM), the hedonic pricing method (HPM), and the travel cost method (TCM) have been applied to capture different benefits (Tyrväinen, 2001; Konijnendijk et al., 2005). Furthermore, approaches such as tree price, Cost-Benefit Analysis have been adopted in assessing urban forest benefits (Tyrväinen, 2001; Konijnendijk et al., 2005).

The modeling for assessment of urban trees

To better identifying and appreciating the ecosystem services provided by urban forests and maximize the tree benefits, various analysis and assessment have been developed and implemented (Leff, 2016; Lin et al., 2019). Many urban forests case studies have been simulated using a wide range of model, they can be roughly divided into two categories: general- purpose model (e.g., ENVI-met, computational fluid dynamics (CFD), Green Cluster Thermal Time Constant (Green CTTC)), and Solar and Longwave Environmental Irradiance Geometry (SOLWEIG), and urban forest-specific models (e.g., i-Tree, CITYgreen) (Lin et al., 2019).

i-Tree is the most dominant model used in urban forest modeling developed by the U.S. Forest Service and its partners in 2006. Of the various i-Tree toolsets, Eco (formerly UFORE) was the most widely used software suite, although case studies can also be found using Street (formerly STRATUM), Hydro, Canopy, and Species (Lin et al., 2019). i-Tree Eco apart from many other assessments and valuation tools that based on the field data to estimate urban and community forest features such as biomass and leaf area and then, based on these properties, quantifies the Ecosystem services of 1) carbon storage and sequestration, (2) air pollution removal, (3) human health effects associated with air pollution removal, (4) heating and cooling energy savings in houses, and (5) stormwater runoff avoided. The system comprises three components: model codes written in computer languages, parameters for the models (e.g., coefficients in model equations), and input data (e.g., weather data) (Tan et al., 2021). So far, i-Tree Eco has been applied in over 21 counties and 264 case studies mostly located in the US and European countries (Lin et al., 2019; Tan et al., 2021).

The previous studies of street trees in Japan

In Japan, the previous studies related to street trees mainly focus on four aspects: the planting and growing environment for street trees; the street trees maintenance and management; the evaluation of streetscape creation by street trees; and ecological benefits of street trees. Hamano (2009), Iizuka (2009), and Nomura (2009) shared the knowledge of the overall status and key challenges of constrained growing space for street trees in Japan.

From the aspect of planting and growing environment for street trees, Ichikawa et al. (2007) and Maeda et al. (2016) surveyed growth of *Cornus florida* were influenced by the sunlight radiation and different site conditions. Ohnuki (1992), Shinnobu (1997), and Takahashi (2008) investigated the different factors of soil environment related to the condition of street trees.

From the aspect of street trees maintenance and management, Kaniwa (1999) explicitly introduced the heavy pruning method that was conducted in Japan. Ide et al. (1983) and Furuno (2014) emphasized the perspective of ecological diversity should be considered in street tree species selection. Nagashima (2014) noted that tree species that are resistant to low solar radiation are suitable for planting in urban areas. Shoda et al. (2020) found that due to the management practices impact the growth rate of street trees which the diameter growth of street trees in Kyoto, Japan was substantially lower than that of nursery-grown trees and street trees in the USA.

Considering the evaluation of streetscape creation by street trees, questionnaire surveys are used in most of the literature, such as Seko (2016) and Matsumoto et al. (2019) based on the questionnaire to clarify the different pruning methods of street trees have different effects on the formation of the landscape beautification and the economic value of the street trees scenery.

In terms of the ecological benefit or ecosystem services, Inoue et al. (1989), Gao et al. (1995), Sakaida (1996), and Shu et al. (2011) used the experiment to demonstrate the effect of street trees or street canopy on the microclimate regulation. Fukui and Nishino (2014) highlighted the ecological benefits provided by street trees as the urban green corridor through the evaluation of the relationship between the planting environment of street trees and birds.

Recently, taking advantage of the trend in the global adaptation of modeling tools to estimate the ecosystem services, Hirabayashi et al. (2016) and (2019) conducted pilot studies about the ecosystem service by street trees in Japan, in which the accuracy of analysis results was enhanced by customizing the i-Tree model.

1.2.2 Main gap

Despite extensive knowledge of factors that influence urban tree health and survival, most research to date has focused on street trees planted in North America and Europe. There is currently a lack of research conducted in Japan, where some of the most densely populated cities in the world are located. For example, to using field-based inventories data to reflect and understand the current status, species composition, age distribution, and major factors that affect street trees.

In addition, although a lot of research brings insight into the ecological function of street trees in Japan, however, lacks a comprehensive approach of research related to street trees to employ ecosystem service management. Moreover, there are still uncertainties in applying US-based ES and associated benefit quantification models in Japan without appropriate modifications.

1.3 The purpose of study

1.3.1 Study site

Kyoto City, the capital of Kyoto Prefecture, is located in the Kansai region of Japan and experiences a humid subtropical climate with hot, wet summers (June–August) and cold, dry winters (December–February). Kyoto City is an ancient city with a history of more than 1200 years, and the urban cores were developed from the layout of the former imperial capital Heian-Kyo, resulting in dense urban infrastructure and cramped streets.

Due to its basin topography, Kyoto experiences the most severe summer heat in Japan, with mean maximum temperatures of around 37 °C in August, the mean annual temperature is 15.9℃, and the annual precipitation of 1491.3mm (Japan Meteorological Agency, 2019). According to the basic plan for greening of Kyoto City, in the central area of Kyoto City, large green spaces, such as Kyoto Gyoen National Garden and Ni-jo Castle, are limited in number and scattered. Street trees situated at the ground level are recognized by city planners as having an integral role as irreplaceable green assets, providing critical ecological connectivity, mitigating negative effects of heat islands, and acting as green corridors (see Fig 1.4) that promote wildlife abundance and diversity. As such, the green corridor zone was selected as the research area because street trees here were identified as crucial green infrastructure with high maintenance needs. This zone encompasses the north to south extent from Kitayama-Dori Street to Jyujo-Dori Street and stretched east to west from Shirakawa-Dori Street to Nishioji-Dori Street (Fig 1.5) (Kyoto City Office, 2010).

Until the end of March 2020, the population of street trees in Kyoto City are about 40,000 and about 830,000 shrubs. Tree species (ratio) of trees are ginkgo (*Ginkgo biloba*) (35%), trident maple (*Acer buergerianum*) (15%), plum/cherry (*Prunus* spp.) (9%), Japanese zelkova (*Zelkova serrata* (Thunb.) Makino.) (8%), flowering dogwood (*Cornus florida* L.) (5%), tuliptree (*Liriodendron tulipifera* L.) tree (4%) (Kyoto City Office, 2021). The Green Policy Promotion Office of Municipal Construction Bureau is responsible for the street trees management and maintenance. Local landscape gardening professionals are responsible for basic tree care services including watering, replacing missing soil, and conducting pruning as well as replacement. Local tree professionals apply different management methods (e.g., pruning) based on considerations for species and planting location conditions. In the past decade, with the promotion of the "Street Tree Supporter System", increasingly citizens are motivated to becoming a steward of the nearby trees where they lived, participating in cleaning fallen leaves, weeding, reporting information on tree diseases and pests (Kyoto City Office, 2021).

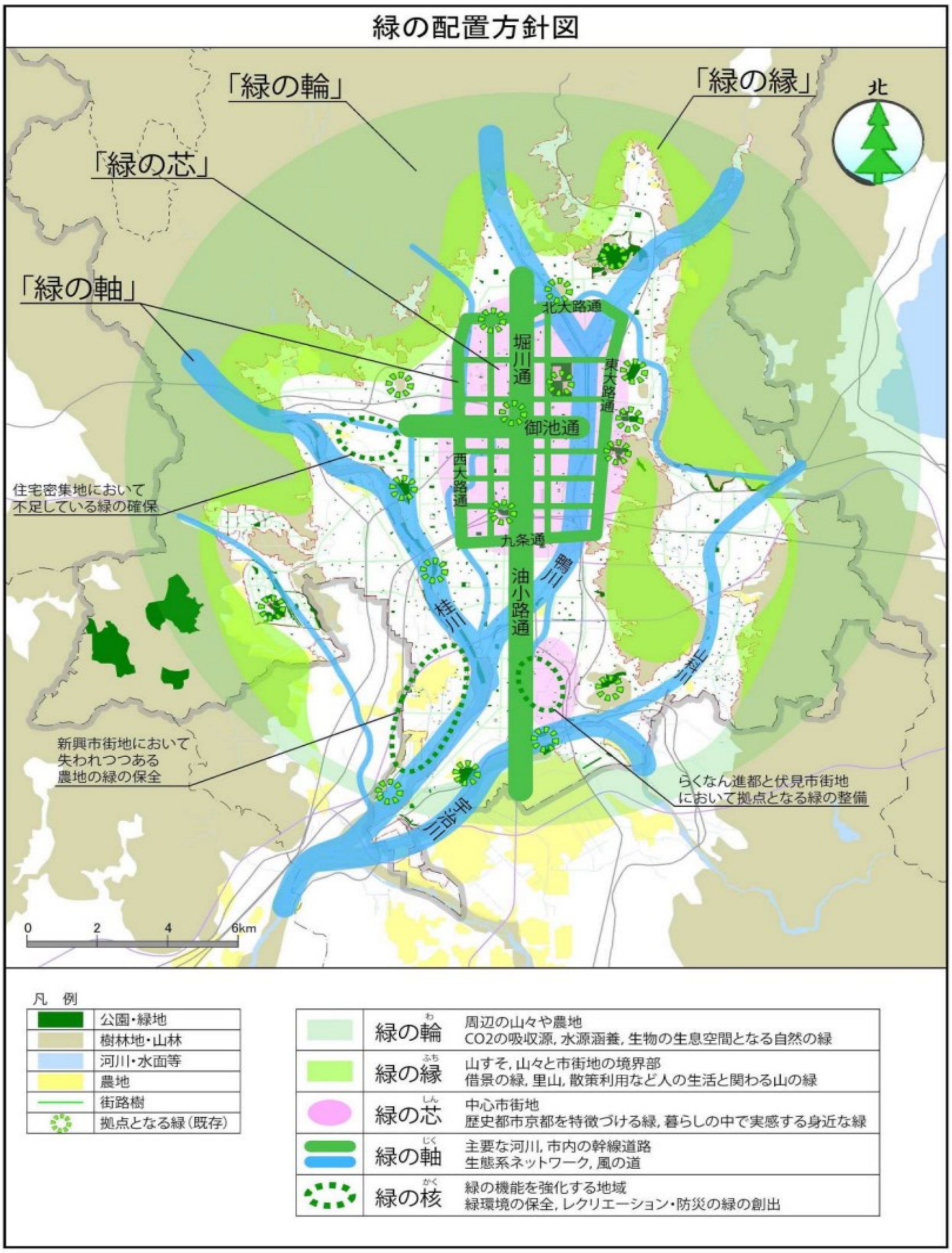


Figure 1. 4 The green corridors (緑の軸) area in Kyoto City (***source***: adopted the basic plan for greening of Kyoto City, 2010)

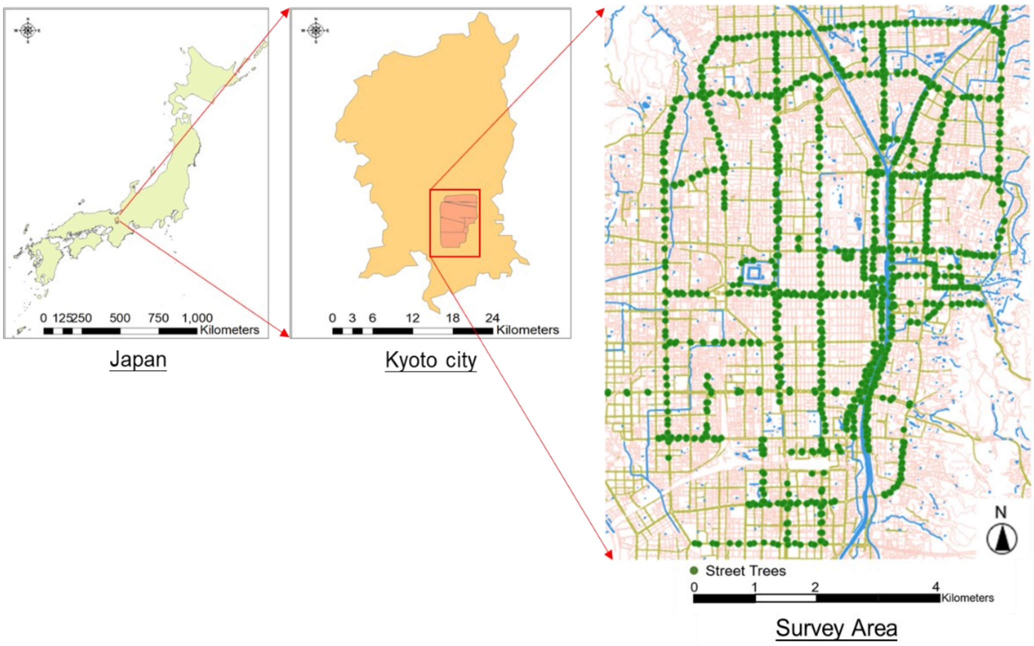


Figure 1. 5 The study area in Kyoto City (***source***: Author)

1.3.2 Main objectives of study

The main purpose of this study was to address the significant gap in urban tree research in Asia by focusing on Kyoto City, Japan. Specifically, we aimed to (1) To analyze the current status of street trees in Kyoto City, including clarify the species composition, health conditions, soil quality, and identify major factors that affect the condition of street trees in restricted planting spaces. (2) To evaluate the ecosystem services provided by street trees in Kyoto city as baseline data though customizing the i-Tree eco models and parameters. (3) To appeal for a better understanding of street trees as green assets in Kyoto City, which could help ensure adequate tree maintenance and lead to future improvements in management and plans

1.4 Methodological framework

1.4.1 Structure of study

This study is organized into five chapters to address the three research questions: (1) what the current status of street trees in Kyoto City is including species composition, health conditions, soil quality, and what factors will affect street trees health. (2) how was the value of ecosystem services provided by Kyoto's Street trees, which can provide the foundation for assessing return on investment in their management. (3) how to establish more comprehensive long-term plans for street trees in Kyoto City. Fig 1.6 demonstrated the structures of this study, Chapter one is focused on introducing the street trees as the provider of ecosystem service in urban areas, as well as the current research and challenges related to street trees, and the objectives, research design, methodological of this research. Chapter two focuses on the perspective of above-ground part of trees to understand and examine the impact of constrained planting environments on the health condition of street trees in Kyoto City. Based on the empirical data of 1230 street trees to identify several tree- and site-related variables that affected tree health. Chapter three focuses on the perspective of below-ground

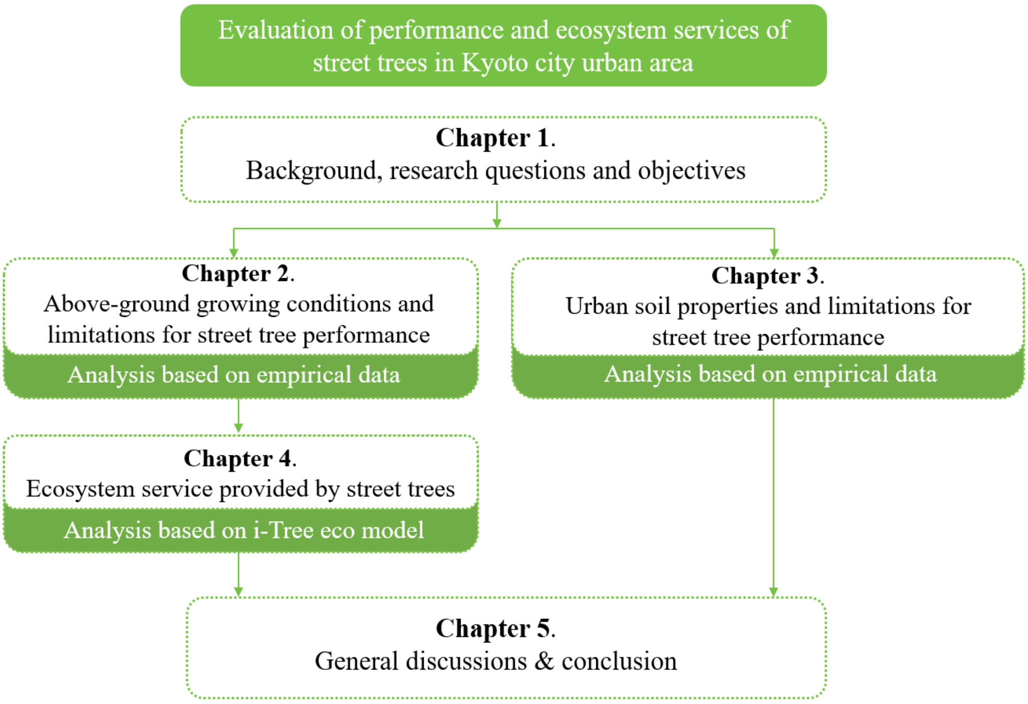


Figure 1. 6 The structure of this thesis

part of trees to understand the soil quality of streetscape in Kyoto City, with an emphasis on evaluating specific soil porosity limitations on the street tree condition, through the empirical data and laboratory analysis. Chapter four applied i-Tree Eco with customized models and parameters for monetarization of the street tree benefits in Kyoto City based on street trees inventory data. A general discussion overall conclusion and recommendation are summarized in chapter five.

1.4.2 Methodologies

***Tree inventory* (*"bottom-up" approach*)**

Based on the field-based tree inventories, the "bottom-up" survey approach, provides detailed data on each tree attributes (such as tree species, numbers, DBH, crown size, location, and conditions) (Leff, 2016). The surge of establishing the urban tree inventories has been performed and supported by rapid developments in North America and European (Nielsen et al., 2014). Inventories could reflect the valuable morphological characteristic, structure, and current situation of trees (e.g., the species suitability based on tree performance) for researchers monitoring changes in tree composition and changes. Moreover, these tree data as parameters are essential input in the modeling and quantification of the ecosystem services and economic values that urban trees provide to the community (Nielsen et al., 2014). In Kyoto City, there is no comprehensive street tree inventory data established. A representative sample-based inventories approach was adopted in our study.

Soil evaluation

Soils are vital to plants growth and health via provide with water, nutrients, and root anchorage. A number of previous studies of the soil profile yield much evidence that the capabilities and limitations of soil for urban greening (Konijnendijk et al., 2005). The evaluation of the ecological characteristics of soil units and their spatial distribution delivers basic information not only to understand the landscape but also to understand specific soil factors for urban planning and for information exchange with policy makers (Konijnendijk et al., 2005). For the purpose of this study, soil physical and chemical experimental methodology was used to distinguish the soil quality of streetscape soils in Kyoto City, with an emphasis on evaluating specific soil porosity limitation on the street tree condition, through the empirical data and laboratory analysis.

Application of i-Tree eco model

i-Tree Eco is one of the flagship products in i-Tree software suites, and designed to use tree inventory data including Tree species, DBH, height, Crown base height, Health condition, Crown width, Land use, Crown %missing, Crown light exposure, Direction & Distance to the nearest constructions, GIS location map, Local weather (like Heat degree day, Cool degree day, Annual precipitation and Air pollution data as input data, cause the model kept the 6800 species their allometric equations in us 11 climate regions, 16 reference cities, based on these equations to quantify forest structure, functions and transfer to values. Forest structure includes tree cover, leaf area index, species composition, and so on shown here. Based on these structures Eco quantifies the functions provided by trees, including air pollution removal, carbon storage and sequestration, and so on. Then these functions are converted to monetary value (see Fig 1.7).

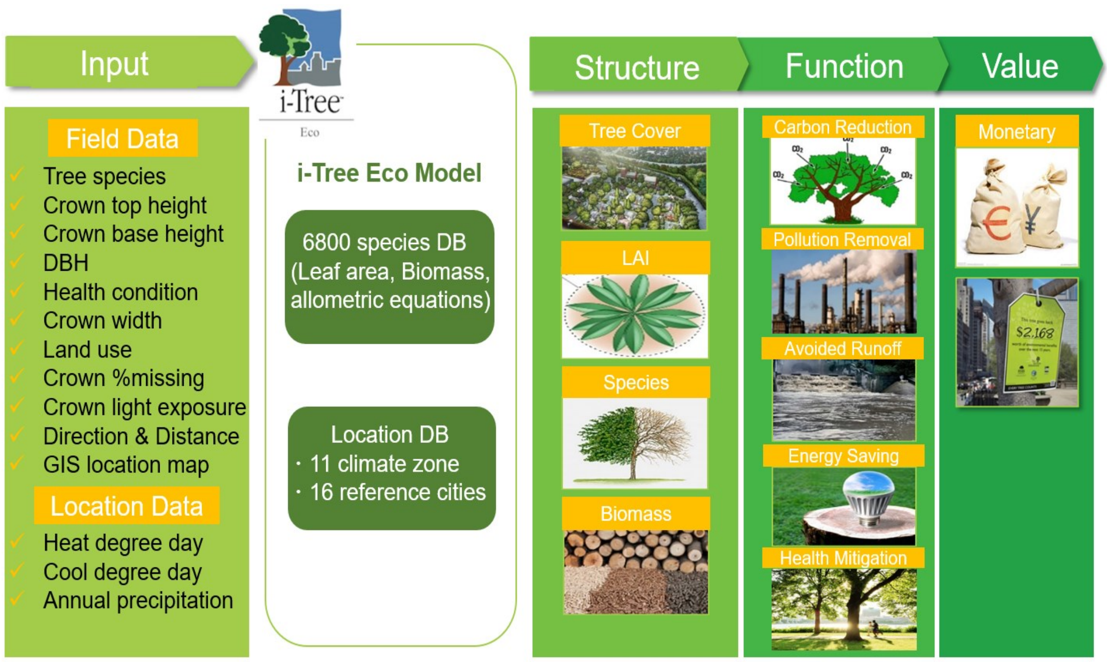


Figure 1. 7 The process flow chart of i-Tree eco model (***source***: Author)

1.5 Reference

Anderson, L. M., Cordell, H. K., 1988. Influence of trees on residential property values in Athens, Georgia (USA): A survey based on actual sales prices. Landscape and urban planning, 15(1-2), 153-164.

Bolund, P., Hunhammar, S., 1999. Ecosystem services in urban areas. Ecological economics, 29(2), 293-301.

Cekstere, G., Osvalde, A., 2013. A study of chemical characteristics of soil in relation to street trees status in Riga (Latvia). Urban Forestry & Urban Greening, 12(1), 69-78.

Cheng, S., McBride, J. R., Fukunari, K., 1999. The urban forest of Tokyo. Arboricultural Journal, 23(4), 379-392.

City of Melbourne. Urban Forest Strategy. https://www.melbourne.vic.gov.au/community/greening-the-city/urban-forest/Pages/urban-forest-strategy.aspx (Accessed on 02/12/2021)

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Van Den Belt, M., 1997. The value of the world's ecosystem services and natural capital. nature, 387(6630), 253-260.

Day, S. D., Bassuk, N. L., 1994. A review of the effects of soil compaction and amelioration treatments on landscape trees. Journal of arboriculture, 20(1), 9-17.

Daily, G. C., 1997. Introduction: what are ecosystem services. Nature’s services: Societal dependence on natural ecosystems, 1(1).

Donovan, G. H., Butry, D. T., 2010. Trees in the city: Valuing street trees in Portland, Oregon. Landscape and urban planning, 94(2), 77-83.

Dover, J. W., 2015. Green infrastructure: incorporating plants and enhancing biodiversity in buildings and urban environments. Routledge.

Elmqvist, T., Setälä, H., Handel, S. N., Van Der Ploeg, S., Aronson, J., Blignaut, J. N., De Groot, R., 2015. Benefits of restoring ecosystem services in urban areas. Current opinion in environmental sustainability, 14, 101-108.

Forrest, M., Konijnendijk, C., 2005. A history of urban forests and trees in Europe. In Urban forests and trees (pp. 23-48). Springer, Berlin, Heidelberg.

Fujii, E., 2019. Street Trees Contribute to the City: Walking on the Marathon Course of the Tokyo Olympics; Iwanami Shoten: Tokyo, Japan, pp. 135–140 (In Japanese).

Fukui, W., Nishino, S., 2014. A case study on relationship between the birds and street trees in Kyoto City, Japan. Journal of the Japanese Society of Revegetation Technology. 40(1), 223-226 (In Japanese).

Furuno, M., Uchida, T., Xue, J., 2014. Effect of flora around street trees on conservation on biological diversity in urban landscape. Journal of the Japanese Society of Revegetation Technology, 40(1), 247-250 (In Japanese).

Gao, W., Sugiyama, H., Ojima, T., 1995. Field study of effect of street and its tree on thermal environment of sidewalks. Journal of Architecture, Planning and Environmental Engineering, 469, 53-64 (In Japanese).

Gilbertson, P., Bradshaw, A. D. 1985. Tree survival in cities: the extent and nature of the problem. Arboricultural Journal, 9(2), 131-142.

Grabosky, J., Bassuk, N., 1995. A new urban tree soil to safely increase rooting volumes under sidewalks. *Journal of Arboriculture*, *21*, 187-187.

Grabosky, J., Bassuk, N., Irwin, L., van Es, H., 1998. Structural soil investigations at Cornell University.

In The landscape below ground II, proceedings of a second international workshop on tree root development in urban soils, International Society of Arboriculture (pp. 203-209).

Gómez-Baggethun, E., Barton, D. N., 2013. Classifying and valuing ecosystem services for urban planning. Ecological economics, 86, 235-245.

Haaland, C., van Den Bosch, C. K., 2015. Challenges and strategies for urban green-space planning in cities undergoing densification: A review. Urban forestry & urban greening, 14(4), 760-771.

Hamano, C., 2009. Subject for draw up a repair precept of street trees. Journal of the Japanese Society of Revegetation Technology 35, 259–261 (In Japanese).

Harris, R. W., 2004. Arboriculture: integrated management of landscape trees, shrubs, and vines (No. Ed. 4). Prentice-Hall International.

Hauer, R. J., Miller, R. W., Ouimet, D. M., 1994. Street tree decline and construction damage. Journal of Arboriculture, 20, 94-94.

Hawver, G. A., Bassuk, N. L., 2007. Soils: The key to successful establishment of urban vegetation. In Urban and Community Forestry in the Northeast (pp. 165-182). Springer, Dordrecht.

Hilbert, D. R., Roman, L. A., Koeser, A. K., Vogt, J., van Doorn, N. S., 2019. Urban tree mortality: a literature review. Arboriculture & Urban Forestry: 45 (5): 167-200., 45(5), 167-200.

Hirabayashi, S., Tan, X., Shibata, S., 2019. Customization of i-Tree Eco's energy saving and health effect models for Japan. Journal of the Japanese Society of Revegetation Technology. 45, 200–203 (In Japanese).

Hirabayashi, S., Tokue, Y., Ito, A., Ellis, A., Hoehn, R., Imamura, F., Morioka, C., 2016. Estimating ecosystem services and their monetary values provided by street trees in Kawasaki ward of Kawasaki city using i-Tree Eco. Journal of the Japanese Society of Revegetation Technology. 42, 4–49 (In Japanese).

Iakovoglou, V., Thompson, J., Burras, L., Kipper, R., 2001. Factors related to tree growth across urban-rural gradients in the Midwest, USA. Urban Ecosystems 5, 71–85.

Ichikawa, K., Hara, Y., Henry, B.P., Storer, A.J., Takeuchi, K., 2007. Planting environment and growing condition of dogwood (Cornus florida) street trees in the 23wards of Tokyo prefecture. Journal of the Japanese Institute of Landscape Architecture. 2007(0), 55-55 (In Japanese).

Ide, M., Nemoto,Y., Ide, H., 1983. Ecological diversity of street trees in Yokohama City. Journal of the Japanese Institute of Landscape Architecture, 47(5), 89-94 (In Japanese).

Iizuka, Y., 2009. Current status of the root system and the planting bases of street trees. Journal of the Japanese Society of Revegetation Technology 35(2), 262-266 (In Japanese).

Iizuka, Y., 2018. Improvement of safety and amenity of street trees. Journal of the Japanese Society of Revegetation Technology 44, 297–301 (In Japanese).

Iizuka, Y., Funakubo, S., 2019. Current status and changes of street trees. Tree and Forest Health 23-2:110-111 (In Japanese).

Inoue, K., Kume, Nobuo., Okuyama, Tomiko., 1989. Model experiments of effects of street trees on microclimate in street canyon. National institute of Agro-Environmental Sciences Report, (4), 89-103 (In Japanese).

Japan Meteorological Agency, 2019. Normal Value (Value for Each Year/ Month) of Meteorological Data (In Japanese) Retrieved from https://www.data.jma.go.jp/obd/stats/etrn/view/annually_s.php?prec_no=61&block_no=47759&year=&month=&day=&view= (Accessed on 01/20/2020).

Jim, C. Y., 1998. Physical and chemical properties of a Hong Kong roadside soil in relation to urban tree growth. Urban Ecosystems, 2(2), 171-181.

Jim, C. Y., 2004. Green-space preservation and allocation for sustainable greening of compact cities. Cities, 21(4), 311-320.

Jim, C. Y., 2005. Monitoring the performance and decline of heritage trees in urban Hong Kong. Journal of environmental management, 74(2), 161-172.

Jim, C. Y., Konijnendijk van den Bosch, C., Chen, W. Y., 2018. Acute challenges and solutions for urban forestry in compact and densifying cities. Journal of Urban Planning and Development, 144(3), 04018025.

Kaniwa, M., 1999. New perspective of street tree pruning. Journal of Green Age 26(5), 14–18 (In Japanese).

Kim, Y. J., Yoo, G., 2021. Suggested key variables for assessment of soil quality in urban roadside tree systems. Journal of Soils and Sediments, 21(5), 2130-2140.

Ko, Y., Lee, J.-H., McPherson, E.G., Roman, L.A., 2015. Factors affecting long-term mortality of residential shade trees: evidence from Sacramento, California. Urban Forestry & Urban Greening 14, 500–507.

Koeser, A. K., Gilman, E. F., Paz, M., Harchick, C., 2014. Factors influencing urban tree planting program growth and survival in Florida, United States. Urban Forestry & Urban Greening, 13(4), 655-661.

Koeser, A.K., Hauer, R., Norris, K., Krouse, R., 2013. Factors influencing long-term street tree survival in Milwaukee, WI, USA. Urban Forestry & Urban Greening 12, 562–568.

Konijnendijk, C. C., Nilsson, K., Randrup, T. B., Schipperijn, J. (Eds.)., 2005. Urban forests and trees: a reference book. Springer Science & Business Media.

Kumar, P., 2012. The economics of ecosystems and biodiversity: ecological and economic foundations. Routledge.

Kume, M., Hioki, Y., 2006. Relationships between vitality of Prunus yedoensis Matsum. and soil hardness in block parks. Japanese Society of Revegetation Technology 32(1), 98-101 (In Japanese).

Kyoto City Official, 2010. The basic plan for green of Kyoto City (In Japanese) https://www.city.kyoto.lg.jp/kensetu/page/0000077122.html (Accessed on 01/20/2020).

Kyoto City Official, 2021. Kyoto City Street Trees Supporter System (In Japanese) https://www.city.kyoto.lg.jp/kensetu/page/0000258130.html (Accessed on 12/20/2021).

Kyoto City Official, 2021. The street trees in Kyoto City (In Japanese) https://www.city.kyoto.lg.jp/kensetu/cmsfiles/contents/0000277/277249/kyotogairoju2020.pdf (Accessed on 12/20/2021).

Leff, M., 2016. The sustainable urban forest: A step-by-step approach. Davey Institute/USDA Forest Service.

Limoges, S., Apparicio, P., 2018. Growing on the street: Multilevel correlates of street tree growth in Montreal. Urban Forestry & Urban Greening 31, 15–25.

Lin, J., Kroll, C. N., Nowak, D. J., Greenfield, E. J., 2019. A review of urban forest modeling: Implications for management and future research. Urban Forestry & Urban Greening, 43, 126366.

Lindsey, P., Bassuk, N., 1992. Redesigning the urban forest from the ground below: a new approach to specifying adequate soil volumes for street trees. Arboricultural Journal, 16(1), 25-39.

Liu, C., Li, X., 2012. Carbon storage and sequestration by urban forests in Shenyang, China. Urban Forestry & Urban Greening, 11(2), 121-128.

Livesley, S.J.; Baudinette, B.; Glover, D., 2014. Rainfall interception and stem flow by eucalypt street trees–The impacts of canopy density and bark type. Urban Forestry & Urban Greening, 13, 192–197.

Lu, J.W.T., Svendsen, E.S., Campbell, L.K., Greenfield, J., Braden, J., King, K.L., Falxa-Raymond, N., 2010. Biological, social, and urban design factors affecting young street tree mortality in New York City. Cities Environ. 3 (1), 1–15.

Maco, S.E., McPherson, E.G., 2003. A practical approach to assessing structure, function, and value of street tree populations in small communities. Journal of Arboriculture 29(2), 84–97.

Maeda, Y., Kawai, T., Tsuchiya, R., Koyama, K., 2016. Growth and sunlight condition assessment of Cornus florida. Tree and Forest Health. 20(3), 138-142 (In Japanese).

Martin, M.P., Simmons, C., Ashton, M.S., 2016. Survival is not enough: The effects of microclimate on the growth and health of three common urban tree species in San Francisco, California. Urban Forestry & Urban Greening 19, 1–6.

Matsumoto, A., Fukui, W., Hikishima, D., 2019. Landscape evaluation and economic value evaluation against landscape creation by two-stage pruning of street trees. Journal of the Japanese Institute of Landscape Architecture, 12(0), 76-82 (In Japanese).

McPherson, E. G., 2007. Benefit-based tree valuation. Arboriculture & Urban Forestry 33 (1): 1-11, 33(1), 1-11.

McPherson, E. G., Nowak, D., Heisler, G., Grimmond, S., Souch, C., Grant, R., Rowntree, R., 1997. Quantifying urban forest structure, function, and value: the Chicago Urban Forest Climate Project. Urban ecosystems, 1(1), 49-61.

McPherson, E. G., Rowntree, R. A., 1993. Energy conservation potential of urban tree planting. Journal of Arboriculture 19(6).

McPherson, E. G., Simpson, J. R., 2003. Potential energy savings in buildings by an urban tree planting programme in California. Urban forestry & urban greening, 2(2), 73-86.

McPherson, E. G., Simpson, J. R., Peper, P. J., Xiao, Q., 1999. Benefits-cost analysis of Modesto's municipal urban forest. Journal of Arboriculture. 25 (5): 235-248., 25(5), 235-248.

MEA, 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.

Million Trees NYC Million Trees NYC. From: https://www.milliontreesnyc.org/html/about/about.shtml (Accessed 12/12/2021)

Mincey, S. K., Hutten, M., Fischer, B. C., Evans, T. P., Stewart, S. I., Vogt, J. M., 2013. Structuring institutional analysis for urban ecosystems: A key to sustainable urban forest management. Urban ecosystems, 16(3), 553-571.

Ministry of Land, Infrastructure, Transport and Tourism, 1960. Road Traffic Act (In Japanese). Available online: https://elaws.e-gov.go.jp/document?lawid=327AC1000000180 (Accessed on 08/12/2021).

Ministry of Land, Infrastructure, Transport and Tourism, 1970. Government Order on Road Design Standards (In Japanese). Available online: https://www.mlit.go.jp/road/sign/kouzourei_kaisetsu.html (Accessed on 08/12/2021).

Moll, G., 1989. The state of our urban forest. American Forests, 95(11/12), 61-64.

Moore, G. M., 2009. Urban trees: worth more than they cost. In Proc. 10th National Street Tree Symp., Univ. Adelaide/Waite Arboretum, Adelaide (pp. 7-14).

Mullaney, J., Lucke, T., Trueman, S. J., 2015. A review of benefits and challenges in growing street trees in paved urban environments. Landscape and Urban Planning, 134, 157-166.

Nagashima, H., Endo, N., Shibuya, K., Sato, S., 2014. Study on roadside trees suitable for planting between tall trees. Journal of the Japanese Society of Revegetation Technology, 40(1), 231-234 (In

Japanese).

Nielsen, A. B., Östberg, J., Delshammar, T., 2014. Review of urban tree inventory methods used to collect data at single-tree level. Arboriculture & Urban Forestry, 40(2), 96-111.

Nilsson, K., Åkerlund, U., Konijnendijk, C. C., Alekseev, A., Caspersen, O. H., Guldager, S., Selikhovkin, A., 2007. Implementing urban greening aid projects–The case of St. Petersburg, Russia. Urban Forestry & Urban Greening, 6(2), 93-101.

Nilsson, K., Sangster, M., Konijnendijk, C. C., 2011. Forests, trees and human health and well-being: Introduction. In Forests, trees and human health (pp. 1-19). Springer, Dordrecht.

Nomura, T., 2009. Beautiful roadside trees scape and the base for tree planting. Journal of the Japanese Society of Revegetation Technology 35(2), 271-276 (In Japanese).

North, E.A., D'Amato, A.W., Russell, M.B., Johnson, G.R., 2017. The influence of sidewalk replacement on urban street tree growth. Urban Forestry & Urban Greening 24, 116–124.

Nowak, D. J., 1994. Air pollution removal by Chicago's urban forest. Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project, 63-81.

Nowak, D. J., Crane, D. E., 2002. Carbon storage and sequestration by urban trees in the USA. Environmental pollution, 116(3), 381-389.

Nowak, D. J., Crane, D. E., Stevens, J. C., 2006. Air pollution removal by urban trees and shrubs in the United States. Urban forestry & urban greening, 4(3-4), 115-123.

Nowak, D. J., Greenfield, E. J., Hoehn, R. E., Lapoint, E., 2013. Carbon storage and sequestration by trees in urban and community areas of the United States. Environmental pollution, 178, 229-236.

Nowak, D. J., Kuroda, M., Crane, D. E., 2004. Tree mortality rates and tree population projections in Baltimore, Maryland, USA. Urban forestry & urban greening, 2(3), 139-147.

Nowak, D. J., McBride, J. R., Beatty, R. A., 1990. Newly planted street tree growth and mortality. Journal of Arboriculture. 16 (5): 124-130., 16(5).

Ohnuki, N., Matsumoto, S., 1992. Basic Studies on Soil Environment for Sound Growth of Street Trees. Journal of the Japanese Institute of Landscape Architecture, 56(1), 39-44 (In Japanese).

Ranganathan, J., Raudsepp-Hearne, C., Lucas, N., Irwin, F., Zurek, M., Bennett, K., West, P., 2008. A Guide for Decision Makers. World Resources Institute.

Raum, S., Hand, K. L., Hall, C., Edwards, D. M., O'Brien, L., Doick, K. J., 2019. Achieving impact from ecosystem assessment and valuation of urban greenspace: The case of i-Tree Eco in Great Britain. Landscape and Urban Planning, 190, 103590.

Roman, L. A., Battles, J. J., McBride, J. R., 2014(a). Determinants of establishment survival for residential trees in Sacramento County, CA. Landscape and Urban Planning, 129, 22-31.

Roman, L.A., J.J. Battles, J.J., McBride. J.R., 2014(b). The balance of planting and mortality in a street tree population. Urban Ecosystems 17:387–404.

Roman, L. A., Conway, T. M., Eisenman, T. S., Koeser, A. K., Barona, C. O., Locke, D. H., Vogt, J., 2021. Beyond 'trees are good': Disservices, management costs, and tradeoffs in urban forestry. Ambio, 50(3), 615-630.

Roman, L. A., Scatena, F. N., 2011. Street tree survival rates: Meta-analysis of previous studies and application to a field survey in Philadelphia, PA, USA. Urban Forestry & Urban Greening, 10(4), 269-274.

Roman, L. A., Walker, L. A., Martineau, C. M., Muffly, D. J., MacQueen, S. A., Harris, W., 2015. Stewardship matters: Case studies in establishment success of urban trees. Urban Forestry & Urban Greening, 14(4), 1174-1182.

Rogers, K., Sacre, K., Goodenough, J., Doick, K., 2015. Valuing London's urban forest: results of the London i-Tree eco project.

Rowntree, R. A., 1984. Ecology of the urban forest—Introduction to Part I. Urban Ecology, 8(1-2), 1-11.

Rowntree, R. A., 1986. Ecology of the urban forest—introduction to part II. Urban Ecology, 9(3-4), 229-243.

Roy, S., Byrne, J., Pickering, C., 2012. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. Urban forestry & urban greening, 11(4), 351-363.

Sakaida, K., 1996. Effect of street trees on urban climate. International association of traffic and safety sciences, 22(1), 32-39. (In Japanese)

Sanders, J.R., Grabosky, J.C., 2014. 20 years later: Does reduced soil area change overall tree growth? Urban Forestry & Urban Greening 13, 295-303.

Salmond, J. A., Tadaki, M., Vardoulakis, S., Arbuthnott, K., Coutts, A., Demuzere, M., Wheeler, B. W., 2016. Health and climate related ecosystem services provided by street trees in the urban environment. Environmental Health, 15(1), 95-111.

Scharenbroch, B. C., Carter, D., Bialecki, M., Fahey, R., Scheberl, L., Catania, M., Raciti, S., 2017. A rapid urban site index for assessing the quality of street tree planting sites. Urban Forestry & Urban Greening, 27, 279-286.

Scharenbroch, B. C., Catania, M., 2012. Soil quality attributes as indicators of urban tree performance. Arboriculture & Urban Forestry, 38(5), 214-228.

Schoenholtz, S. H., Van Miegroet, H., Burger, J. A., 2000. A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. Forest ecology and management, 138(1-3), 335-356.

Seko, S., Fukui, W., Hamada, K., 2016. The Achievements and Tasks of Two-Step Pruning of Street Trees for Landscape Beautification in Kyoto City. Journal of the Japanese Institute of Landscape Architecture, 9, 58-63 (In Japanese).

Seko, S., 2017. A study on planting environment of street trees and the consciousness of residents to conflicts between street tree root growth and hardscape. [D]. Univ. of Kyoto Prefectural (In Japanese)

Shinnobu, Y., Nishimura, T., 1997. Soil environment of street trees planting curb in Kochi district. Kochi University Faculty of Agriculture Seminar Forest Report (In Japanese).

Shoda, T., Imanishi, J., Shibata, S., 2020. Growth characteristics and growth equations of the diameter at breast height using tree ring measurements of street trees in Kyoto City, Japan. Urban Forestry & Urban Greening, 49, 126627.

Shu, M., Hioki, Y., Ohtagaki, R., 2011. An evaluation of green shade effects of zelkova serrata using thermal image. Journal of the Japanese Society of Revegetation Technology. 37(1), 245-248 (In Japanese).

Sæbø, A., Benedikz, T., Randrup, T. B., 2003. Selection of trees for urban forestry in the Nordic countries. Urban Forestry & Urban Greening, 2(2), 101-114.

Takahashi, T., Oikawa, N., Okada, H., Kobayashi, T., 2008. The relationships among growth of street trees and chemical and physical characteristics of planting ground in Matsudo city, Chiba prefecture. Journal of the Japanese Society of Revegetation Technology, 34(1), 231-234 (In Japanese).

Tan, X., Hirabayashi, S., Shibata, S., 2021. Estimation of Ecosystem Services Provided by Street Trees in Kyoto, Japan. Forests, 12(3), 311.

Tan, Z., Lau, K. K. L., Ng, E., 2016. Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment. Energy and Buildings, 114, 265-274.

Tyrväinen, L., 2001. Economic valuation of urban forest benefits in Finland. Journal of environmental management, 62(1), 75-92.

Udawatta, R. P., Henderson, G. S., 2003. Root distribution relationships to soil properties in Missouri oak stands: A productivity index approach. Soil Science Society of America Journal, 67(6), 1869-1878.

Ulmer, J. M., Wolf, K. L., Backman, D. R., Tretheway, R. L., Blain, C. J., O'Neil-Dunne, J. P., Frank, L. D., 2016. Multiple health benefits of urban tree canopy: The mounting evidence for a green prescription. Health & place, 42, 54-62.

United Nations Department of Economic and Social Affairs (DESA)., 2018. World urbanization prospects 2018.

Van Doorn, N. S., McPherson, E. G., 2018. Demographic trends in Claremont California's street tree population. Urban Forestry & Urban Greening, 29, 200-211.

Xiao, Q., McPherson, E. G., Ustin, S. L., Grismer, M. E., 2000a. A new approach to modeling tree rainfall interception. Journal of Geophysical Research: Atmospheres, 105(D23), 29173-29188.

Xiao Q., McPherson E. G., Ustin S. L., Grismer M. E., Simpson J. R., 2000b. Winter rainfall interception by two mature open-grown trees in Davis, California. Hydrological Processes 14(4):763–784.

Yang, J., Zhou, J., Ke, Y., Xiao, J., 2012. Assessing the structure and stability of street trees in Lhasa, China. Urban Forestry & Urban Greening, 11(4), 432-438.

2. Above-ground growing conditions and limitations for street tree performance in Kyoto City

2.1. Introduction

Street trees are widely identified as an essential component of urban green infrastructure, providing multifunctional benefits to city-dwellers (Jim and Zhang, 2013). In addition to the most obvious effect of enhancing the aesthetics of streetscapes, research has also highlighted the ecological benefits provided by street trees from environmental, social, and economic perspectives, including air quality improvement, carbon storage and sequestration, stormwater management, energy conservation, human physical health improvements, and increases in property values (Maco and McPherson, 2003; Nowak et al., 2006; Roy et al., 2012; Mullaney et al., 2015). The long-term ecological benefits generated by street trees greatly depend on tree survival, healthy growth, and longevity (Ko et al., 2015; Martin et al., 2016). For example, trees will lose their normal ability to absorb CO_2 when they suffer environmental stresses such as subjection to hot, dry weather (McPherson and Simpson, 1999). Moreover, larger and healthy trees contain significantly more biomass in their root systems and possess a greater capacity to store and sequester CO_2—thus improving air quality—than smaller or diseased trees (McPherson et al., 1994; McPherson and Simpson, 1999). To establish and sustain healthy trees, ensuring the effective delivery of the long-term benefits they provide, information concerning how street tree management and care may affect their condition and longevity is essential for urban tree managers and planners (Koeser et al., 2013).

Nevertheless, the urban densification process and infill development, accompanied by limitations on available growing space and advancing climate change, present a stressful environment for street trees, affecting their growth and longevity (Haaland and van den Bosch, 2015; Jim et al., 2018). Street trees tend to have lower mean life expectancy and higher mortality rates than the same species grown in non-urban areas (Moll, 1989; Roman and Scatena, 2011; Mullaney et al., 2015). To date, urban tree research has identified various biophysical and anthropogenic factors that affect street tree conditions. Biophysical factors include the types of tree species, tree size, and age, which are all closely related to the diameter at breast height (DBH) and soil condition (Iakovoglou et al., 2001; Nowak et al., 2004; Lu et al., 2010; Koeser et al., 2013). Known anthropogenic factors include associations with surrounding land use, urban design form (e.g., street setting), vandalism, and stewardship (Nowak et al., 2004; Lu et al., 2010; Ko et al., 2015; Limoges and Apparicio, 2018). Many studies have also suggested that a constrained growing condition is one of the most critical factors negatively affecting the growth of urban trees (Sæbø et al., 2003; Sanders and Grabosky, 2014, Dover, 2015; Mullaney et al., 2015). It is common to find accounts of conflicts between tree expansion and nearby urban infrastructure. As tree diameters increase, the probability and severity of damage increase. The use of restricted planting spaces leads to further pressures such as soil compaction, insufficient water and nutrients, and the need for severe pruning which may weaken tree growth and vigor. North et al. (2017) compared the tree growth, calculated as basal area increment, pre-and post-sidewalk construction, and found street trees planting in areas with a width of less than 1.25 m showed no growth recovery after 5 years of sidewalk construction activities, while larger tree pits positively correlated with better tree condition (Lu et al., 2010; Koeser et al., 2013). Despite extensive knowledge of factors that influence urban tree health and survival, most research to date has focused on street trees planted in North America and Europe (Hilbert et al., 2019). There is currently a lack of research conducted in Asia, where some of the most densely populated cities in the world are located (Nagendra and Gopal, 2010).

In addition, growing evidence suggests that trees and green spaces are lost due to densification of urbanized areas in many Asian cities, and urban tree growth is now largely confined to cramped urban core areas (Haaland and van den Bosch, 2015; Jim et al., 2018). This situation is prominent in compact, highly developed urban areas in countries like Japan. Street trees have been downgraded to accessories of the street by the road act of Japan (Ministry of Land, Infrastructure, Transport and Tourism, 1952). In many instances, roadside planting space is often the first area to be sacrificed for complex underground infrastructure developments (e.g., installing gas pipes, cables, sewers), creating separated, narrow tree pits instead of continuous planting strips (Hamano, 2009). Iizuka (2018) indicated that the population of street trees in Japan is stable, both in terms of stocking level and low overall replacement rates over the past 15 years; with this trend, a conflict between inadequate planting space and mature large-diameter trees will likely become increasingly prominent. Additionally, the abundance of above-ground utility poles and overhead power grids present in most parts of Japan, which restricts the space for sidewalks, resulting in the need for periodic heavy pruning of street trees. As a result, street tree conditions will be impacted by the chronic stresses, including confined growth space, conflict with above-ground infrastructures, and frequent pruning (Kaniwa, 1999). Accordingly, studies on the response of street trees in these locations under constrained planting conditions are urgently needed.

The main purpose of this chapter was to address the significant gap in urban tree research in Asia by focusing on Kyoto City, Japan. Our study examines the health of street trees in Kyoto City to provide a detailed assessment that can be used to improve management and planning decisions. Specifically, we aimed to (1) Assess the current status of street trees in Kyoto City, including species composition and health conditions, (2) Identify major factors that affect the condition of street trees in restricted planting spaces. The results will not only fill a critical knowledge gap by providing data from field surveying of street tree distributions in Kyoto City, but will also advance our knowledge of urban forestry in constrained planting environments and facilitate comprehensive recommendations on future street tree master planning.

2.2. Materials and methods

2.2.1. Study site

Kyoto City, the capital of Kyoto Prefecture, is located in the Kansai region of Japan and experiences a humid subtropical climate with hot, wet summers (June–August) and cold, dry winters (December–February). Kyoto City is an ancient city with a history of more than 1200 years, and the urban cores were developed from the layout of the former imperial capital Heian-Kyo, resulting in dense urban infrastructure and cramped streets. Numerous alley roads with widths of under 4 m still exist in the inner-city area. Data from 2012 collected by the Kyoto municipal government show that 40 km of alley roads remain, which cover about 13,000 routes in the urban areas of Kyoto City (Kyoto City Office, 2012). Moreover, this municipal report also noted that Japan has too many utility poles and cables compared to other countries. Although the government of Japan has recognized the elimination of utility poles as an urgent issue, the cost burden associated with such a drastic change in built infrastructure has prevented the advancement of the "No Power Pole Revolution" (The Japan Times, 2017). Pervasive utility poles remain scattered across the streets of urban areas result in highly congested street space.

Due to its basin topography, Kyoto experiences the most severe summer heat in Japan, with mean maximum temperatures of around 37 °C in August (Japan Meteorological Agency, 2019). In the central area of Kyoto City, large green spaces, such as Kyoto Gyoen National Garden and Ni-jo Castle, are limited in number and scattered. Street trees situated at the ground level are recognized by city planners as having an integral role as irreplaceable green assets, providing critical ecological connectivity, mitigating negative effects of heat islands, and acting as green corridors that promote wildlife abundance and diversity (Kyoto City Office, 2010).

2.2.2. Street tree management in Kyoto City

In Kyoto City, street trees are managed and maintained by the Green Policy Promotion Office of Municipal Construction Bureau. Local landscape gardening professionals are responsible for basic tree care services including watering, replacing missing soil, and conducting pruning as well as replacement. Local tree professionals apply different management methods (e.g., pruning) based on considerations for species and planting location conditions. In the past decade, with the promotion of the "Street Tree Supporter System", increasingly citizens are motivated to becoming a steward of the nearby trees where they lived, participating in cleaning fallen leaves, weeding, reporting information on tree diseases and pests (Kyoto City Office, 2021).

2.2.3. Selection of sample trees

Currently, there is no comprehensive street tree inventory data maintained by Kyoto City. A representative sampling approach was adopted in our study. According to the basic plan for greening of Kyoto City, the green corridor zone was selected as the research area because street trees here were identified as crucial green infrastructure with high maintenance needs. This zone encompasses the north to south extent from Kitayama-Dori street to Jyujo-Dori street and stretched east to west from Shirakawa-Dori street to Nishioji-Dori street (Kyoto City Office, 2010). The

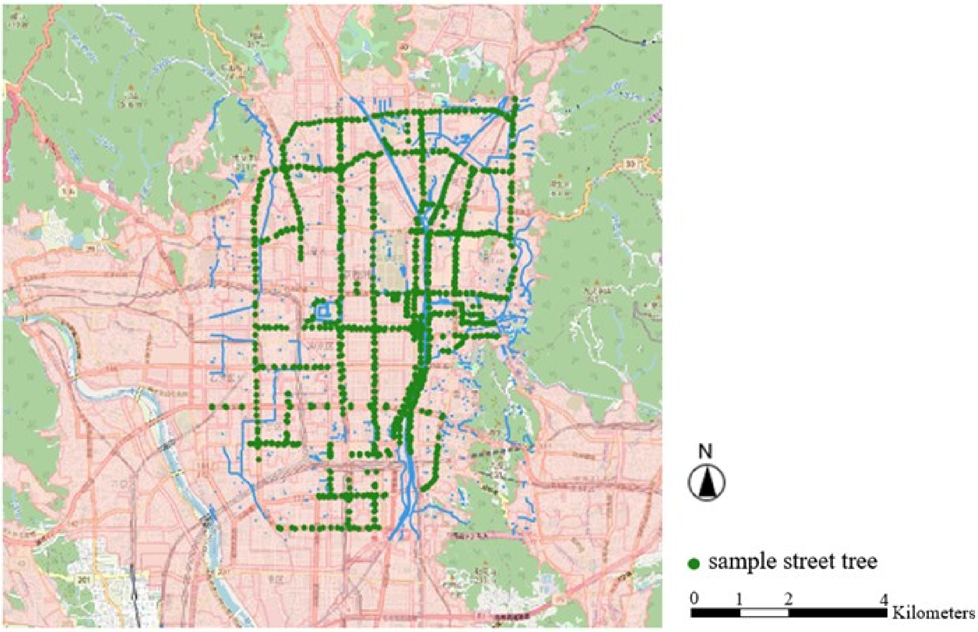


Figure 2. 1 Study site in Kyoto City, Japan (***source***: Author)

latest 1:25,000-scale Kyoto City park and street trees map was first obtained from the Green Policy Promotion Office of the Kyoto City Construction Bureau, containing only species names and the location of road where the street tree was planted in the central city. A pre-sampling step was implemented to estimate the number of street trees in the selected survey area using Google Earth. Approximately 10% of the trees on each street were sampled by equal distance to generate the tree inventory. An original field survey of 1233 trees in 41streets was conducted from June to October 2018 (see Appendix 1), consisting of 27 species, classified into 18 families and 19 genera. including 11 invasive species. The tree samples of 1230 were used in this Chapter due to three individual samples with incomplete data collection being excluded from the analysis. The sampling survey was designed to reflect all species under the constraint of more intensively developed portions of urban areas. Each tree location was identified using a Global Positioning System (Oregon 600, Garmin, KS, USA). (Fig 2. 1).

2.2.4. Data collection

Tree- and site-related data

A field survey form was used to record information in the field (Appendix 2). Tree- and site-related factors that could potentially influence tree growth conditions were also collected from each tree during the field survey. The factors were divided into four groups: tree information, streetscape features, planting site, and constraint condition (see Table 2.1).

Tree health rating

The tree decline rating method was adopted to assess the tree health condition (Hori, 2014). The method is recognized as a standard tree condition assessment by the Japan Greenery Research and Development Center which is widely applied in research institutions, and tree expert companies in Japan (Japan Greenery Research and Development Center, 2014). The method originally included twelve parameters. In our study, the “tree shape” parameter was removed as it was deemed unsuitable for estimating managed street tree with unnatural shapes. The remaining eleven parameters including tree vigor, density of branches and foliage, leaf color, damage of lower crown, damage or decay of tree bark, leaf (bud) size, damage of upper crown, tree base condition, bark metabolism, branch extension amount, and presence or absence of trunk body sprout and basal shoot were evaluated in the rating form (Appendix 3). Each parameter had five-level evaluation criteria, from 0 (best) to 4 (worst), and the evaluation criteria for each level have well-defined visual traits of trees. One person did all tree condition ratings by observation from the ground level in several directions. The formulae used in the calculation was:

$$H = (1 - \frac{\sum_{i=1}^{11} hi}{44}) \times 100, \quad (1)$$

where h_i is the rating of each parameter and H is the tree health score.

2.2.5. Data analysis

Multivariate linear regressions were used to investigate tree- and site-related factors associated with the health condition of street trees, in accordance with the methods used in previous work (Vrecenak et al., 1989; Iakovoglou et al., 2001; Quigley, 2004), via the SPSS Statistics version 19 (IBM Corp., NY, USA). Data from the seven most common tree species were used in these models (N = 1139): ginkgo (*Ginkgo biloba*), trident maple (*Acer buergerianum*), Japanese zelkova (*Zelkova serrata (Thunb.) Makino.*), plum/cherry (*Prunus spp.*), tuliptree (*Liriodendron tulipifera L.*), flowering dogwood (*Cornus florida L.*), and London planetree (*Platanus* × *acerifolia (Aiton) Willd.*) (Table 2.2).

The model was based on the following equation:

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \cdots \alpha_i X_i + \mu, \quad (2)$$

where Y is the health score of street trees, X_i is the independent variable representing the tree- and site-related factor data, α_i is the slope, and α_0 and μ represent the constant and random error, respectively.

Table 2. 1 The description of street tree data collected by field survey in Kyoto City.

Data item		***Description of variables***
Tree information	Species	*Ginkgo biloba* (47.8%), *Acer buergerianum* (14.1%), *Zelkova serrata* (8.1%), *Prunus* spp.[a] (7.1%), *Liriodendron tulipifera* (6.2%), *Cornus florida* (4.8%), *Platanus × acerifolia* (4.2%), others (7.7%)
	DBH (cm) [b]	Numerical
	Total tree height (m)	Numerical
Streetscape feature	Road categories [c]	Wide road (16.4%), Medium road (70.7%), Narrow road (12.9%)
	Geographic orientation	NS (41.3%), EW (58.7%)
	Dedicated cycle route	Presence (24.8%), Absence (75.2%)
	Adjacent land use classification	Residential (40.4%), Commercial (40.3%), Industrial (2.8%), Educational & Institutional (5.8%), Open space (10.7%)
Planting site	Tree pit type	Single tree pit, Tree strip
	Tree pit pattern	Bare (38.8%), Concrete (1.7%), Flower bed (4.7%), Grass (18.2%), Shrubs (36.6%)
	Tree grate/guard	Absence (83.8%), Iron (10.4%), Concrete/stone (5.8%)
	Crown Light exposure [d]	2 sides (6.6%), 3 sides (14.9%), 4 sides (73.3%), 5 sides (5.2%)
Constraint condition	Obstructions within a 2m distance [e]	Absence (26.7%), One (44.6%), Two (24.9%), Three (3.8%)
	Pruning intensity [f]	Weak (30.5%), Medium (55.5%), Strong (14.0%)
	Tree pit size (m^2)	Numerical
	Width of sidewalk (m) [g]	Numerical

[a] *Prunus* spp. including *Prunus × yedoensis* Matsum., *Prunus jamasakura* Siebold, *Prunus spachiana* (Lavall,e ex H.Otto) Kitam.

[b] Diameter at 1.37 m above ground level were measured. In case of multi-stemmed trees: the diameter of up to six stems, each at least 2.54 cm, were measured separately; if a tree had more than six such stems, a single diameter was measured at 30.5 cm height (i-Tree Eco Field Guide, 2020).

[c] Road categories were classified as: wide road (> 4 lanes), medium road (2 < lanes ≤ 4), narrow road (≤ 2 lanes). [d] Crown light exposure was classified on a scale of 0–5, as tree crowns receive direct sunlight from five sides (north, south, east, west, and upward) (Bechtold, 2003). [e] Number of obstructions (e.g., traffic signs, overhead cables, electricity, and ground obstructions). [f] Pruning intensity was rated as three levels (Appendix 11). [g] Measurements based on three scenarios: (a) tree pit: standard length of 1.5m with varying width (≤ 1.5m); (b) tree pit: standard length of 1.8m with varying width (≤ 1.8m); (c) planting strip: standard width of 1m with varying length (≥ 2.5m).

As the qualitative independent variables (dummy variables) cannot be accommodated directly by multivariate linear regression analysis (Data item 5-14, Table 2.2), we recoded dummy variables to allow incorporation of the data into the linear model by coding a set of dummy regressors as 0 or 1. In general, for a dummy variable with n categories, n-1 dummy regressors were recorded, with the "omitted" category serving as a benchmark and coded 0 for all dummy regressors in the set to allow comparison with the other categories (Fox, 2015).

The models were constructed using the stepwise probability criteria of *F* to enter <= 0.050， and probability of *F* to remove >= 0.100. Independent variables entered step by step in the analysis were not significant for deletion. In each model, the variance inflation factors (VIF) value from 1.00 to 4.80 (<=10) generated by using Collinearity Diagnostics function indicated there were no issues with potential multicollinearity (Aljandali, 2017). We compared the model fit based on the R^2 value and ANOVA produced in each model. Higher R^2 with lower standard error of the estimate represents better fitting. The *F* ratio of explanatory variables in the selected model is statistically significant at 0.001 confidence level, which indicates that the variables included in the model are correct.

Our initial attempt was unsuccessful when we added the independent dummy variable of tree species to the maximal (full) models due to the heavily over-dispersed residuals. As such, seven species were analyzed separately given the noted differences in the tree species management methods. Species-specific sets of models are presented in (Appendix 4-10). The adjusted R^2 value of the final model we used between 0.377 to 0.807, which could explain 37.7%-80.7% of the variation in the tree health condition, indicated moderate explanatory power of the model as a whole (Table 2.3). Since each model was statistically significant with minimum error of the estimate, the acceptance of the variables included in the model helps us to draw useful insight into tree growing in complex biophysical and anthropogenic situations in Kyoto City.

Table 2. 2 The descriptive statistics of seven common tree species data used in regression model.

	Ginkgo biloba*	***Acer buergerianum****	***Zelkova serrata***	***Prunus* spp.[a]**	***Liriodendron tulipifera ****	***Cornus florida****	***Platanus×acerifolia****
Data item	n=588	n=174	n=100	n=88	n=76	n=59	n=51
1.Mean tree height (m)[b]	8.55(1.45)	8.72(1.28)	11.97(3.27)	7.03(1.75)	8.42(2.28)	4.90(1.12)	9.78 (1.28)
2.Mean DBH (cm)[c]	26.14(8.78)	29.11(9.75)	35.47(16.21)	34.24(18.52)	19.13(10.14)	10.39(3.83)	29.17 (5.75)
3.Mean tree pit size (m2)[d]	10.09(3.68)	4.56(1.28)	4.80(1.63)	11.33(3.78)	3.29(1.83)	2.69(1.21)	3.18(1.28)
4.Mean width of sidewalk (m)[e]	3.33(1.17)	3.50(0.73)	6.64(3.33)	3.57(1.90)	3.78(0.63)	3.68(0.90)	3.60(0.70)
5.Road categories (W/M/N) (%)[f]	6.1/78.3/15.6	6.3/89.7/4.0	36.0/50.0/14.0	2.3/35.2/62.5	40.3/54.5/5.2	5.0/53.3/41.7	23.0/63.5/13.5
6.Geographic orientation (NS/EW)(%)[g]	62.8/37.2	53.7/46.3	54.0/46.0	75.0/25.0	36.4/63.6	28.3/71.7	40.4/59.6
7.Dedicated cycle route (%)[h]	14.6(P)/85.4(A)	69.7(P)/30.3(A)	43.0(P)/57.0(A)	5.6(P)/94.3(A)	76.6(P)/23.4(A)	11.7(P)/88.3(A)	1.9(P)/98.1(A)
8.Adjacent land use classification (%)[i]	45.2(R)/40.6(C)/ 0.8(I)/5.6(E)/7.8(O)	50.9(R)/44.6(C)/ 0.5(I)/4.0(O)	32.0(R)/38.0(C)/ 13.0(E)/17.0(O)	11.4(R)/8.0(C)/ 72.6(E)/8.0(O)	2.6(R)/71.4(C)/ 26.0(I)	50.0(R)/23.3(C)/5.0(I)/ 10.0(E)/11.7(O)	21.2(R)/61.5(C)/ 13.5(I)/3.8(E)
9.Tree pit type (%)[j]	71.6(S)/28.4(T)	45.1(S)/54.9(T)	14.0(S)/86.0(T)	13.6(S)/86.4(T)	74.0(S)/26.0(T)	85.0(S)/15.0(T)	90.4(S)/9.6(T)
10.Tree pit pattern (%)[k]	45.7(B)/2.9(C)/2.3(F)/ 18.5(G)/30.6(S)	34.3(B)/1.7(C)/ 16.0(G)/48.0(S)	11.0(B)/23.0(F)/ 15.0(G)/51.0(S)	18.2(B)/3.4(F)/ 19.3(G)/59.1(S)	45.5(B)/5.1(F)/ 20.8(G)/28.6(S)	48.3(B)/6.7(F)/ 20.0(G)/25.0(S)	67.3(B)/1.9(C)/ 21.2(G)/9.6(S)
11.Tree grate/guard (%)[l]	86.1(A)/8.3(I)/5.6(C)	90.3(A)/5.7(I)/4.0(C)	96.0(A)/2.0(I)/2.0(C)	92.0(A)/8.0(C)	72.7(A)/26.0(I)/1.3(C)	38.4(A)/28.3(I)/33.3(C)	57.7(A)/42.3(I)
12.Crown light exposure (%)[m]	1.3(2)/3.6(3)/ 94.4(4)/0.7(5)	1.1(2)/12.6(3)/ 84.6(4)/1.7(5)	22.0(2)/21.0(3)/ 10.0(4)/47.0(5)	29.5(3)/61.4(4)/ 9.1(5)	1.3(2)/3.9(3)/ 88.3(4)/6.5(5)	3.3(2)/16.7(3)/80.0(4)	3.8(2)/19.3(3)/ 76.9(4)
13.Obstructions in 2m distance (%)[n]	20.3(A)/45.1(1)/ 30.0(2)/4.6(3)	5.7(A)/52.6(1)/ 35.4(2)/6.3(3)	65.0(A)/35.0(1)	55.7(A)/39.8(1)/ 4.5(2)	37.7(A)/49.3(1)/ 13.0(2)	33.3(A)/58.3(1)/8.4(2)	9.6(A)/28.9(1)/ 51.9(2)/9.6(3)
14.Pruning intensity (%)[o]	33.0(W)/56.6(M)/ 10.4(S)	21.7(W)/65.7(M)/ 12.6(S)	9.0(W)/49.0(M)/ 42.0(S)	36.4(W)/52.3(M)/ 11.3(S)	15.6(W)/66.2(M)/ 18.2(S)	90.0(W)/10.0(M)	17.3(W)/55.8(M)/ 26.9(S)

*Denote non-native species.

[a] *Prunus* spp. including *Prunus × yedoensis* Matsum., *Prunus jamasakura* Siebold, *Prunus spachiana* (Lavall,e ex H.Otto) Kitam.

[b,c,d,e] The standard deviation were given in parenthesis.

[f] Variables include wide road (W), Medium road (M), Narrow road (N); [g] Variables include North-South direction (NS), East-West direction (EW); [h] Variables include Presence (P), Absence (A);

[i] Variables include Residential (R), Commercial (C), Industrial (I), Education & institution (E), Open space (O); [j] Variables include Single tree pit (S), Tree strip (T);

[k] Variables include Bare (B), Concrete (C), Flower bed (F), Grass (G), Shrubs (S); [l] Variables include Absence (A), Iron (I), Concrete/Stone (C); [m] Variables include 2 sides (2), 3 sides (3), 4 sides (4), 5 sides (5)

[n] Variables include Absence (A), One (1), Two (2), Three (3); [o] Variables include Weak (W), Medium (M), Strong (S).

Table 2. 3 Final models and regression results (only the variables that showed significant results are presented).

	Ginkgo biloba		*Acer buergerianum*		*Zelkova serrata*		*Prunus* spp.[a]		*Liriodendron tulipifera*		*Cornus florida*		*Platanus×acerifolia*	
Variables	Coeff.	95%CI	Coeff.	95%CI	Coeff.	95%CI	Coeff.	95%CI	Coeff.	95%CI	Coeff.	95%CI	Coeff.	95%CI
Pruning intensity [b]														
Medium	-1.159**	-1.726, -0.592	-1.075**	-2.211, 0.061	-1.962*	-4.109, 0.185	-0.875*	-2.821, 1.071	-3.389**	-5.702, -1.077	-5.884*	-9.570, -2.197	-0.443**	-3.975, 3.088
Strong	-3.278**	-4.196, -2.361	-5.032**	-6.626, -3.437	-5.457*	-8.515, -2.399	-4.628*	-7.741, -1.515	-8.239**	-11.304, -5.173			-13.239**	-18.555, -7.924
Tree pit size	0.025**	0.019, 0.032	0.010*	0.003, 0.017			0.012*	0.004, 0.020	0.020*	0.006, 0.034	0.138*	0.002, 0.053	0.092†	0.022, 0.162
Adjacent land use [c]														
Commercial	-0.733*	-1.393, 0.073	-1.300*	-2.297, -0.304	3.653*	1.476, 5.829			-0.100†	-6.184, 5.985			-5.850*	-9.100, -2.599
Industrial	-3.925*	-6.154, -1.696	-1.563*	-6.990，3.863					-9.895†	-18.514, -1.275			-10.253*	-17.668, -2.839
Education	-0.252*	-1.384, 0.880			3.436*	0.880, 5.991								
Open space	0.584*	-0.703, 1.870	-0.752*	-5.240, 3.737	0.618*	-1.973, 3.209								
Tree grate/guard [d]														
Iron steel	0.999*	0.122, 1.876			2.143*	0.444, 11.973			2.956*	1.052, 4.860	2.060†	-0.660, 4.781		
Concrete/stone	0.916*	-0.268, 2.099			0.725*	-3.100, 6,654			4.775*	-1.701, 11.251	2.726†	0.037, 5.416		
Width of sidewalk	0.006*	0.001, 0.011	0.019**	0.011, 0.026			0.024*	0.010, 0.038						
Total tree height	0.005**	0.003, 0.008											0.015*	0.005,0.025
Dedicated cycle route [e]														
Presence					2.533†	0.092, 4.974			8.755*	2.515, 14.995				
Tree pit pattern [f]														
Flower bed	1.908*	0.559, 3.256									2.666†	-1.025, 6.357		
Grass	0.805*	0.082, 1.529									2.334†	0.200, 4.467		
Shrubs	0.270*	-0.634, 1.174									1.655†	-0.983, 4.293		
Concrete	-1.220*	-2.822, 0.381												
CLE [g]														
5 sides	6.446*	2.502, 10.390			4.749†	0.696, 8.802								
4 sides	2.140*	0.587, 3.694			2.004†	-1.406, 5.414								
3 sides	1.020*	-0.713, 2.753			1.572†	-1.240, 4.384								
DBH	-0.066**	-0.104, -0.028												
Tree pit type [h]														
Single tree pit	-4.482**	-5.745, -3.220												
Adjusted R^2	0.377		0.462		0.571		0.560		0.593		0.704		0.807	

†, *, and ** denote significance at the 0.05, 0.01, and 0.001 probability levels, respectively.
[a] *Prunus* spp. Including *Prunus × yedoensis* Matsum., *Prunus jamasakura* Siebold, *Prunus spachiana* (Lavall,e ex H.Otto) Kitam. [b] compared to benchmark "Pruning intensity: weak",
[c] compared to benchmark "Adjacent land use: residential", [d] compared to benchmark "Tree grate/grate: absence", [e] compared to benchmark "Dedicated cycle route: absence"
[f] compared to benchmark "Tree pit pattern: bare", [g] compared to benchmark "Crown light exposure: 2 sides", [h] compared to benchmark "Tree pit type: tree strip"

2.3. Results

2.3.1. Health condition of street trees

The 1230 tree sampled included 27 species in 19 genera from 18 families. The health condition of trees was classified into five categories based on the tree health score: excellent (100-94); good (93-89); fair (88-80); poor (79-65); dying (≤64). The lowest recorded tree condition score was 55, and the highest was 94. In sampled trees, 19.9% could be classified as excellent condition. Trees in good and fair condition accounted for the majority of those sampled (32.0% and 42.9%, respectively), and trees classified as poor and dying accounted for 5.0% and 0.2%, respectively (Table2.4). In terms of species differences (Fig 2.2), the six common species showed good adaptability to the urban environment. As a species native to Japan, *Prunus* spp. showed the best growth with the highest proportion of excellent trees compared to other species, whereas *P.* × *acerifolia* showed the worst results with no excellent condition individuals and 6.0% classified as dying.

Table 2. 4 The health conditions of 1230 street trees by five categories in Kyoto City.

	Excellent (100-94)	Good (93-89)	Fair (88-80)	Poor (79-65)	Dying (≤64)
n	245	394	528	61	2
%	19.9	32.0	42.9	5.0	0.2

Figure 2. 2 Proportion of different health condition classifications of the seven most-common street tree species in Kyoto city.

2.3.2. Determinants for tree health

Eleven predictors showed statistically significant relationships with street tree health. The order of the number of species in which the variables entered to the regression model from high to low was pruning intensity, tree pit size, adjacent land use, presence/absence of tree grate or guard, width of sidewalk, tree height, presence/absence of dedicated cycle route, tree pit pattern, crown light exposure, DBH and tree pit type (Table 2.3).

Pruning intensity

Pruning showed an inverse effect on tree vitality in all seven species ($p < 0.01$). Compared to weak pruning levels (as the benchmark), significant coefficients of moderate and strong pruning were negative. In terms of species differences, the impact of heavy pruning was most pronounced in *P. × acerifolia* (Coeff. of -13.239, $p < 0.001$), while the species that had the smallest association was *G. biloba* (Coeff. of -3.278, $p < 0.001$).

Tree pit size

Tree pit size was strongly associated with the condition of six species: *G. biloba* (Coeff. of 0.025, $p < 0.001$), *A. buergerianum* (Coeff. of 0.010, $p < 0.01$), *Prunus* spp. (Coeff. of 0.012, $p < 0.01$), *L. tulipifera* (Coeff. of 0.020, $p < 0.01$), *C. florida* (Coeff. of 0.138, $p < 0.01$), and *P. × acerifolia* (Coeff. of 0.092, $p < 0.05$). There was also a statistically significant interaction between the effects of tree pit size and pruning intensity on tree condition (ANOVA, F_2, 1130 = 2.850, $p = .023$).

Adjacent land use

The results indicated that adjacent land use significantly associated with tree condition of five species: *G. biloba* ($p < 0.01$), *A. buergerianum* ($p < 0.01$), *Z. serrata* ($p < 0.01$), *L. tulipifera* ($p < 0.05$), and *P. × acerifolia* ($p < 0.01$). Street trees in residential areas (used as the benchmark) showed better condition than those in industrial and commercial areas. However, *Z. serrata* did not follow this trend, instead of showing a greater probability of being in excellent condition in commercial areas (Coeff. of 3.653, $p < 0.01$).

Tree grate or guard

The presence of tree grates or guards increased the health condition of four species: *G. biloba* ($p < 0.01$), *Z. serrata* ($p < 0.01$), *L. tulipifera* ($p < 0.01$), and *C. florida* ($p < 0.05$).

Width of sidewalk

The width of the sidewalk positively influenced the health condition of three species: *G. biloba* (Coeff. of 0.006, $p < 0.01$), *A. buergerianum* (Coeff. of 0.019, $p < 0.001$), and *Prunus* spp. (Coeff. of 0.024, $p < 0.01$).

Tree height and DBH

When comparing tree health with tree size, the results of *G. biloba* seem paradoxical as tree height and DBH showed statistically significant inverse relationships with tree health. Better tree condition was associated with increased total tree heights for both *G. biloba* (Coeff. of 0.005, $p <$

0.001) and *P.* × *acerifolia* (Coeff. of 0.015, $p < 0.01$). Tree health condition and diameter correlated significantly among the species with *G. biloba* (Coeff. of -0.066, $p < 0.001$) exhibiting the lower tree conditions when they had larger diameters.

Dedicated cycle route

Street trees of *Z. serrata* (Coeff. of 2.533, $p < 0.05$) and *L. tulipifera* (Coeff. of 8.755, $p < 0.01$) showed better healthy performance when planted in the road with presence of dedicated cycle route.

Tree pit patterns

The data from *G. biloba* ($p < 0.01$) and *C. florida* ($p < 0.05$) suggest that street trees have a greater chance of increased health if surrounded by flowerbeds, grass, or shrubs rather than concrete paving blocks and bare (used as the benchmark).

Crown light exposure (CLE)

Intuitively, crown light exposure will influence tree health. When solar radiation declines, photosynthesis tends to decrease. However, only two species, *G. biloba* ($p < 0.01$) and *Z. serrata* ($p < 0.05$), were significantly affected by crown light exposure, presumably because 78.5% of the street trees received adequate solar radiation (CLE=4-5).

Tree pit type

Compared to tree strip type (as the benchmark), *G. biloba* (Coeff. of -4.482, $p < 0.001$) planting in single tree pit showed worse condition.

2.4. Discussion

Overall, the majority of street trees in Kyoto City perform well in the stressful urban environment, demonstrating that the species present in the city have strong tolerance for restricted planting conditions. As a possible exception to this, *P.* × *acerifolia* may be intolerant of the harsh urban conditions of Kyoto City (Fig 2.3). One interpretative difference in growing space conditions distinguished from other species was severe smaller tree pit sizes of *P.* × *acerifolia* (Table 2.2), which may deteriorate the tree vigor. In European and North American cities, *P.* × *acerifolia* occur frequently, often planted as street and boulevard trees (McBride, 2017). In Japan, since the Meiji Era, *P.* × *acerifolia* were imported as the first stage street tree species for its qualities with high survival and fast-growing, providing high levels of shade (Cheng et al., 1999). However, in the past two decades, frequent pruning practice and restricted growing space have suppressed the healthy growth of *P.* × *acerifolia* and the species is susceptible to disease—like the canker caused by *Neofusicoccum parvum*, identified in tree specimens in Tokyo and Saitama in 2003 and 2012—and insect infestations, such as that of *Corythucha ciliate (Say)* in Kyoto City in 2007 and 2008 (Ueyama and Tokumaru, 2013; Motohashi et al., 2016). The poor condition generally seen in *P.* × *acerifolia* is consistent with observations from other regions in Japan, including Hokkaido, Tokyo, Saitama, Aichi and Kyushu Region (Ueyama and Tokumaru, 2013; Motohashi et al., 2016). Although, many reports revealed that due to the rapid growth rate and high management expenditure for required pruning, the common street tree selection of *Platanus* spp. trees in Japan were gradually replaced by *C. florida*, because the public prefers species with aesthetic value and low maintenance need for

Figure 2. 3 Street tree examples in constrained planting space having potential conflict with sidewalks and other infrastructure in Kyoto city: (a) *Platanus* × *acerifolia* and (b) *Ginkgo biloba.* ***(source*:** Author)

slower growth (Cheng et al., 1999; Watanabe, 2016). In the future, to improve the sustainability of street trees growing in the constrained environment, the concept of "right tree right place" should be emphasized on street tree selection in Kyoto City. As suggested by urban forestry experts, we should put the appropriate species in suitable locations to make the most benefits provided by trees (Gangloff, 1999; Flowers and Gerhold, 2000). For example, Magarik (2020) indicated that practitioners have managed the potential of conflict with utility poles and wires from large shade trees by replacing them with small-statured trees.

The difference of determinants for street tree health among the seven species derived from the final model results, offering evidence of tree species should be considered as a predictor of tree condition, which concurs with previous research (Nowak et al., 2004; Koeser et al., 2013; Koeser et al., 2014). Another possible predictor is different tree management strategies (e.g., tree pruning, watering, and fertilizer addition) adopted based on different street tree species. We could not investigate this further because of uneven sample numbers per species and specific tree management actions that we were unable to discern on-site. Further research is therefore needed to investigate how the effects of tree management vary by species and physiological-ecological characteristics.

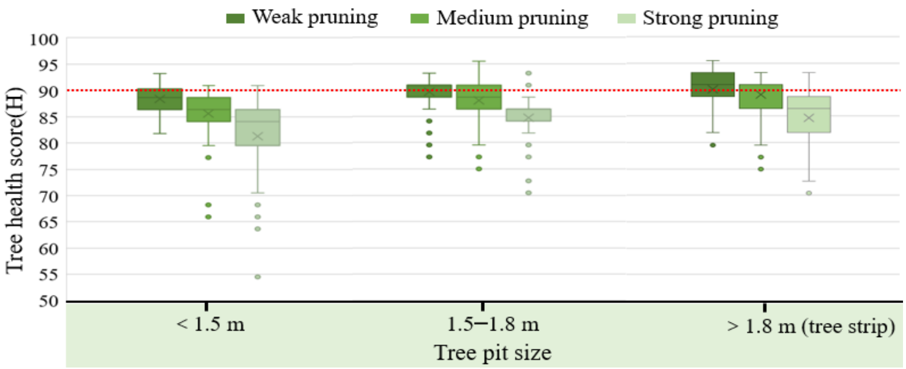


Figure 2. 4 Comparison of street tree health score (H) by tree pit size (m) for pruning level.

In terms of the order of importance of different factors identified by our statistical models (Table 2.3), we found that pruning intensity and tree pit size most commonly significantly affected street tree conditions in almost seven species. Also, the statistically significant interaction between the effects of these two factors on tree condition again highlighted the tree vigor affected by constraint-related factors in Kyoto City. Fig 2.4 illustrates how the health score of the total sample of street trees varies with interactions between tree pit size and pruning intensity. The distribution of condition scores of trees growing in the planting strip category with weak pruning was highest with most trees scoring above 90 while trees planted in the narrow tree pits (< 1.5m) with strong pruning scored mostly below 85.

A result from our model that appeared counterintuitive was that the presence of obstructions was insignificantly associated with tree condition. This observation has been noted in previous research (Nowak et al., 1990; Limoges and Apparicio, 2018) where it was suggested that the presence of obstructions necessitating pruning better explain low street tree condition as this reduces the photosynthesis capacity of the tree crown, reducing growth. Our observations that tree pit size significantly affects tree vigor is in line with previous studies (Berrang et al., 1985; Hauer et al., 1994; Lu et al., 2010; Koeser et al., 2013; Sanders and Grabosky, 2014; North et al., 2017) and could be explained by the restricted planting spaces providing insufficient soil volume for root expansion and preventing air and water from moving nutrients into street tree root zones. Beatty and Heckman (1981) proposed that the most common problems associated with urban tree growth include lack of water, nutrient deficiency, and soil compaction. In Japan, narrow space available for root growth has been widely recognized as the crucial issue for long-term street tree growing (Karizumi, 2010). With the spreading of the tree roots in the restricted planting pits, most of the soil will become consolidated; consequently, tree root growth will cause pavement and sidewalk upheaval. Additionally, the width of the sidewalk affects tree health, with wider sidewalks providing benefits such as providing more open space for growth and through the prevention of vandalism from pedestrian traffic.

Regarding the adjacent land use factors influencing tree conditions, our data found that trees planted in residential areas showed the best condition and this observation is similar to those found in previous studies (Nowak et al., 1990; Nowak et al., 2004; Lu et al., 2010; Ko et al., 2015). In contrast, *Z. serrata* appears to contradict this trend in our study. This may be explained by the fact that the majority of *Z. serrata* in the residential areas were planted in the median strip of road which means that they received heavy pruning. Conversely, commercial areas provide adequate space for *Z. serrata* to grow. Despite most previous work highlighted the adjacent land use influencing the tree performance may be due to neighboring human activities and tree care stewardship (e.g., Nowak et al., 1990; Nowak et al., 2004; Lu et al., 2010; Limoges and Apparicio, 2018). However, as Hilbert et al. (2019) pointed out, land use categories may covary with other unmeasured factors that more directly impact tree mortality and health, and differing land uses may actually reflect differing maintenance regimes. In the future, there is still a need for this study to further investigate the differences in stewardship management awareness among different land use. For example, Breger et al. (2019) assessed qualitative stakeholder interview data to elucidate the stewardship network and thereby explain quantitative survival monitoring results.

The good condition of street trees in Kyoto City may show that appropriate municipal management practices have been put in place. To balance the aesthetics provided by street trees and the cleaning burden from fallen leaves, a new pruning method called two-stage pruning (see Appendix 12) has been implemented in Kyoto City since 2011(Matsumoto et al., 2019), in which pruning occurs in the autumn and winter every two years. In place of traditional pruning methods, weak pruning is conducted before and after leaves change color to reduce the damage to street trees. Our results also show that installing tree pit guards is an effective way to improve tree health under harsh living conditions. This has been shown in previous work (Lu et al., 2010) where it was also suggested that to some extent, guards prevent soil compaction and vandalism of street trees by pedestrians or inadvertent damage from vehicles. At the same time, the presence of dedicated cycle route potentially regulates the flow of pedestrians and bicycles through the environment surrounding the tree.

Finally, biophysical factors were also found to be important in our study, with several showing significant impacts on tree health. For example, adequate solar radiation contributes to good street tree health. In terms of tree height and DBH, the explanation for the divergence of our result is unclear. Moreover, the coefficient value of tree height (0.005 and 0.015) and DBH (-0.066) (Table 4), therefore evidence for their effect was not strong. Many previous research has explored tree longevity difference across tree size classes and tree age stages (Nowak et al.,1990; Nowak et al.,2004; Roman et al., 2014; Ko et al., 2015); our study could not do so due to several possible reasons, including: a) the uniformity of tree height is emphasized in street trees in Kyoto City, and trunk-top pruning has been undertaken to reduce the conflict with overhead power lines. Tree planting year (tree age) cannot be identified simply by tree height. b) trees will have different growth characteristics and equations due to different geographical environments conditions, and management practices. Shoda et al. (2020) found that DBH growth of street trees in Kyoto City was substantially lower than that of street trees in the USA. Therefore, it might not be possible to apply tree size and growth model developed for one country (e.g., USA) in Japan. Thus, future investigation for detailed analysis is required.

2.5. Conclusion

This chapter provides an initial understanding of the real-world impacts of multiple factors associated with planting in the constrained environment of a highly urbanized Asian city with limited growing space on street tree health. In particular, we identified excessive pruning and limited tree pit size as having impacted the performance of Kyoto city's street trees. Appropriate tree care management practices implemented by municipal authorities and communities are playing a key role in ensuring the long-term survival of the city's street trees. Our finding that *P. ×acerifolia* is more strongly stressed by constrained growing conditions than other species suggests the need to consider replacing this tree in the city's new street tree plan. Additionally, our results revealed some potential recommendations that may be useful for practitioners. For example, planting trees on the streets having the dedicated cycle route and adding flowerbeds or shrubs are more likely to prevent trampling and unconscious damage from pedestrians. To maximize the effectiveness of street tree planting decisions in Kyoto City, we suggest a need for strategies including careful tree-friendly planting designs along the streets and the selection of appropriate tree species with narrow crowns. Implementing these strategies could help mitigate declines in tree health and promote the environmental benefits of urban green spaces.

2.6. Reference

Aljandali, A., 2017. Multivariate methods and forecasting with IBM® SPSS® statistics. New York, NY: Springer.

Beatty, R.A., Heckman, C.T., 1981. Survey of urban tree programs in the United States. Urban Ecology 5, 81–102.

Bechtold, W.A., 2003. Crown position and light exposure classification—an alternative to field-assigned crown class. Northern Journal of Applied Forestry 20, 154–160.

Berrang, P., Karnosky, D.F., Stanton, B.J., 1985. Environmental factors affecting tree health in New York City. Journal of arboriculture 11, 185–189.

Breger, B. S., Eisenman, T. S., Kremer, M. E., Roman, L. A., Martin, D. G., Rogan, J., 2019. Urban tree survival and stewardship in a state-managed planting initiative: A case study in Holyoke, Massachusetts. Urban Forestry & Urban Greening, 43, 126382

Cheng, S., McBride, J. R., Fukunari, K., 1999. The urban forest of Tokyo. Arboricultural Journal, 23(4), 379-392.

Dover, J.W., 2015. Green infrastructure: incorporating plants and enhancing biodiversity in buildings and urban environments. Routledge, London.

Flowers, D. E., Gerhold, H. D., 2000. Replacement of trees under utility wires impacts attitudes and community tree programs. Journal of Arboriculture, 26(6), 309-318

Fox, J., 2015. Applied regression analysis and generalized linear models. Sage Publications, CA.

Gangloff, D.,1999. Ten Years and Counting-When it comes to tree planting, stone soup and strange bedfellows make for good partnerships. American Forests, 104, 5-5

Haaland, C., van den Bosch, C.K., 2015. Challenges and strategies for urban green-space planning in cities undergoing densification: A review. Urban Forestry & Urban Greening 14, 760–771.

Hamano, C., 2009. Subject for draw up a repair precept of street trees. Journal of the Japanese Society of Revegetation Technology 35, 259–261 (In Japanese).

Hauer, R. J., Miller, R. W., Ouimet, D. M., 1994. Street tree decline and construction damage. Journal of Arboriculture, 20, 94-94.

Hilbert, D. R., Roman, L. A., Koeser, A. K., Vogt, J.,van Doorn, N. S., 2019. Urban tree mortality: a literature review. Arboriculture & Urban Forestry 45 (5): 167-200.

Hori, T., 2014. Diagonosis Method of Tree Health. Kodansha Ltd, Tokyo (In Japanese).

Iakovoglou, V., Thompson, J., Burras, L., Kipper, R., 2001. Factors related to tree growth across urban-rural gradients in the Midwest, USA. Urban Ecosystems 5, 71–85.

Iizuka, Y., 2018. Improvement of safety and amenity of street trees. Journal of the Japanese Society of Revegetation Technology 44, 297–301 (In Japanese).

i-Tree Eco Field Guide, 2020. https://www.itreetools.org/documents/274/EcoV6.FieldManual.2020.07.23.pdf (Accessed on 04/01/2021).

Japan Greenery Research and Development Center, 2014. The tree decline rating survey. http://www.jpgreen.or.jp/kyoukyu_jyouhou/gijyutsu/j_shindan/shindan03.html (In Japanese) (Accessed on 04/07/2021).

Japan Meteorological Agency, 2019. Normal Value (Value for Each Year/ Month) of Meteorological Data (In Japanese) Retrieved from https://www.data.jma.go.jp/obd/stats/etrn/view/annually_s.php?prec_no=61&block_no=47759&year=&month=&day=&view= (Accessed on 01/20/2020).

Jim, C.Y., Konijnendijk van den Bosch, C., Chen, W.Y., 2018. Acute Challenges and Solutions for Urban Forestry in Compact and Densifying Cities. Journal of Urban Planning and Development 144, 04018025.

Jim, C.Y., Zhang, H., 2013. Species diversity and spatial differentiation of old-valuable trees in urban Hong Kong. Urban Forestry & Urban Greening 12, 171–182.

Kaniwa, M., 1999. New perspective of street tree pruning. Journal of Green Age 26(5), 14–18 (In Japanese).

Karizumi, N., 2010. The Latest Illustrations of tree roots. Seibundo Shinkosha Publ. Co., Tokyo (In Japanese).

Ko, Y., Lee, J.-H., McPherson, E.G., Roman, L.A., 2015. Factors affecting long-term mortality of residential shade trees: evidence from Sacramento, California. Urban Forestry & Urban Greening 14, 500–507.

Koeser, A., Hauer, R., Norris, K., Krouse, R., 2013. Factors influencing long-term street tree survival in Milwaukee, WI, USA. Urban Forestry & Urban Greening 12, 562–568.

Koeser, A.K., Gilman, E.F., Paz, M., Harchick, C., 2014. Factors influencing urban tree planting program growth and survival in Florida, United States. Urban Forestry & Urban Greening 13, 655–661.

Kyoto City Official, 2010. The basic plan for green of Kyoto City (In Japanese) https://www.city.kyoto.lg.jp/kensetu/page/0000077122.html (Accessed on 01/20/2020).

Kyoto City Official, 2012. The policy of strategy for dense urban areas in the historical city of Kyoto (In Japanese) https://www.city.kyoto.lg.jp/tokei/page/0000124869.html (Accesssed on 01/20/2020).

Kyoto City Official, 2021. The Green Policy Promotion Office of Kyoto Municipal Construction Bureau (In Japanese) https://www.city.kyoto.lg.jp/kensetu/soshiki/10-8-0-0-0.html (Accesssed on 04/1/2021).

Limoges, S., Apparicio, P., 2018. Growing on the street: Multilevel correlates of street tree growth in Montreal. Urban Forestry & Urban Greening 31, 15–25.

Lu, J.W.T., Svendsen, E.S., Campbell, L.K., Greenfeld, J., Braden, J., King, K.L., Falxa-Raymond, N., 2010. Biological, social, and urban design factors affecting young street tree mortality in New York City. Cities Environ. 3 (1), 1–15.

Maco, S.E., McPherson, E.G., 2003. A practical approach to assessing structure, function, and value of street tree populations in small communities. Journal of Arboriculture 29, 84–97.

Magarik, Y. A., Roman, L. A., Henning, J. G., 2020. How should we measure the DBH of multi-stemmed urban trees?. Urban Forestry & Urban Greening 47, 126481.

Martin, M.P., Simmons, C., Ashton, M.S., 2016. Survival is not enough: The effects of microclimate on the growth and health of three common urban tree species in San Francisco, California. Urban Forestry & Urban Greening 19, 1–6.

Matsumoto, A., Fukui, W., Hikishima, D., 2019. Landscape evaluation and economic value evaluation against landscape creation by two-stage pruning of street trees. Journal of the Japanese Institute of Landscape Architecture 12(0), 76-82 (In Japanese).

McBride, J. R., 2017. The World's Urban Forests. Springer, Cham, Switerland.

McPherson, E.G., Simpson, J.R., 1999. Carbon dioxide reduction through urban forestry. Gen. Tech. Rep. PSW-171. Albany, CA. US Department of Agriculture, Forest Service, Pacific Southwest Research Station.

McPherson, G.E., Nowak, D.J., Rowntree, R.A., 1994. Chicago's urban forest ecosystem: results of the Chicago Urban Forest Climate Project. Gen. Tech. Rep. NE-186. Radnor, PA. US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Ministry of Land, Infrastructure, Transport and Tourism, 1952, The road act of Japan (In Japanese) https://elaws.e-gov.go.jp/document?lawid=327AC1000000180 (Accessed on 07/20/2021).

Moll, G., 1989. The state of our urban forest. American Forests 95, 61–64.

Motohashi, K., Yoshino, S., Higuchi, H., Nikaido, Y., Ukida, S., Kanda, M., 2016. Canker of Platanus × acerifolia caused by Neofusicoccum parvum. Tree and Forest Health 20, 187–196 (In Japanese).

Mullaney, J., Lucke, T., Trueman, S.J., 2015. A review of benefits and challenges in growing street trees in paved urban environments. Landscape and Urban Planning 134, 157–166.

Nagendra, H., Gopal, D., 2010. Street trees in Bangalore: Density, diversity, composition and distribution. Urban Forestry & Urban Greening 9, 129–137.

North, E.A., D'Amato, A.W., Russell, M.B., Johnson, G.R., 2017. The influence of sidewalk replacement on urban street tree growth. Urban Forestry & Urban Greening 24, 116–124.

Nowak, D.J., Crane, D.E., Stevens, J.C., 2006. Air pollution removal by urban trees and shrubs in the United States. Urban Forestry & Urban Greening 4, 115–123.

Nowak, D.J., Kuroda, M., Crane, D.E., 2004. Tree mortality rates and tree population projections in Baltimore, Maryland, USA. Urban Forestry & Urban Greening 2, 139–147.

Nowak, D.J., McBride, J.R., Beatty, R.A., 1990. Newly planted street tree growth and mortality. Journal of Arboriculture 16, 124–130.

Quigley, M.F., 2004. Street trees and rural conspecifics: Will long-lived trees reach full size in urban conditions? Urban Ecosystems 7, 29–39.

Roman, L.A., Battles, J.J., McBride, J.R., 2014. Determinants of establishment survival for residential trees in Sacramento County, CA. Landscape and Urban Planning 129, 22–31.

Roman, L.A., Scatena, F.N., 2011. Street tree survival rates: Meta-analysis of previous studies and application to a field survey in Philadelphia, PA, USA. Urban Forestry & Urban Greening 10, 269–274.

Roy, S., Byrne, J., Pickering, C., 2012. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. Urban Forestry & Urban Greening 11, 351–363.

Sanders, J.R., Grabosky, J.C., 2014. 20 years later: Does reduced soil area change overall tree growth? Urban Forestry & Urban Greening 13, 295-303.

Shoda, T., Imanishi, J., Shibata, S., 2020. Growth characteristics and growth equations of the diameter at breast height using tree ring measurements of street trees in Kyoto City, Japan. Urban Forestry & Urban Greening, 49, 126627.

Sæbø, A., Benedikz, T., Randrup, T.B., 2003. Selection of trees for urban forestry in the Nordic countries. Urban Forestry & Urban Greening 2, 101–114.

The Japan Times, 2017. Koike's plan for Tepco to remove utility poles in Tokyo an olympian task. https://www.japantimes.co.jp/news/2017/04/03/business/koikes-plan-tepco-remove-utility-poles-tokyo-olympian-task/ (Accesssed on 04/1/2021).

Ueyama, H., Tokumaru, S., 2013. Seasonal Prevalence of Corythucha ciliata (Say) (Heteroptera: Tingidae) in Kyoto city. Japan Applied Entomology and Zoology 57, 177–183 (In Japanese).

Vrecenak, A., Vodak, M., Fleming, L., 1989. The influence of site factors on the growth of urban trees. Journal of Arboriculture 15, 206–209.

Watanabe, K., 2016. The history of street trees and the future. Civil engineering consultant: 273, 10-13 (In Japanese).

3. Urban soil properties and limitations for street tree performance in Kyoto, City

3.1. Introduction

Tree planting in cities has been recognized widely as an indispensable urban green infrastructure in enhancing the aesthetic of streetscape and furnishing a broad range of ecological benefits (Dover, 2015; Mullaney et al., 2015). The raising densification process and intensive human activities occurring in the urban center led to the attendant problems of degraded urban habitats and limited interstitial space for the urban trees (Haaland and van den Bosch, 2015; Jim et al., 2018). The harsh and restricted roadside planting conditions pose major challenges to urban trees including poor soil quality; restricted above and below-ground growing space; pollutants; and conflicts with infrastructures (Jim et al., 2018, Jim, 2019). However, in urban-tree planting studies, the evaluation of the subsurface portion is usually received cursory attention compared to the above-ground realm (Jim,1998b). Millions of trees planted along streets are accommodated in tree pits, many of which suffer from constrained rooting space and soil limitation (Mullaney et at., 2015; Jim, 2018). Patterson et al. (1980) suggested that almost 80% of urban-greening problems can be attributed to the soil environment. The soil that interacts most intimately with tree roots, are important as growth media for urban trees, providing nutrients (e.g., water, minerals, and oxygen) and anchorage to root system (Hawver and Bassuk, 2007). The understanding and assessment of urban soil quality is imperative for establish and sustain the longevity of urban trees (Konijnendijk et al., 2005; Scharenbroch and Catania, 2012; Kim and Yoo, 2021).

The properties of soils in urban region differ substantially from those of their natural counterparts due to the consequence of anthropogenic influences and management practices (Craul, 1985; Konijnendijk et al., 2005; Scharenbroch and Catania, 2012; Jim, 2019). The urban soils are extremely heterogeneous, and have modified soil structure, reduced organic matter contents, elevated pH and salinity to degrade urban tree growth and health (Short et al, 1986; Konijnendijk et al., 2005; Scharenbroch and Catania, 2012; Ghosh et al., 2016). The previous studies of the soil profile in relation to urban tree performance (e.g., establishment, growth, longevity) yields much evidence that showing soil physical and chemical analytic methodology as an important tool to examine soils for their suitability for urban trees (Jim,1998a; 1998b; Konijnendijk et al., 2005; Hawver and Bassuk, 2007; Scharenbroch and Catania, 2012; Kim and Yoo, 2021). The importance of soil physical properties to tree condition is represented by the many literatures shown the soil texture and bulk density large effect on growth of trees (e.g., Jim,1998a; 1998b; Harris et al.,2004; Scharenbroch and Catania, 2012; Scharenbroch et al., 2017). For example, texture affects not only soil's structure but also water relation, aeration and soil compaction (Konijnendijk et al., 2005; Hawver and Bassuk, 2007). Soil chemical properties, especially the indicators of pH and nutrients influence the tree growth (Jim,1998a; Schoenholtz et al., 2000; Udawatta and Henderson 2003; Kim and Yoo, 2021).

In addition, soil compaction is cited as a primary constraint to urban tree growth (Patterson, 1977; Craul,1992; Day and Bassuk, 1994; Jim, 1998b, Hawver and Bassuk, 2007). Compacted soil associated with restricted aeration, poor drainage slows or halts root penetration, resulting in increased branching and radial thickening of roots (Day and bassuk,1994). Roadside trees were widely beset by soil compaction due to the limited rooting space, especially where trees are placed in the tree pits (Jim, 2018). This situation can be extremely challenging in the highly cramped urban area in Japan. In many instances, roadside planting space in Japan is often the first area to be sacrificed for complex underground infrastructure developments (e.g., installing gas pipes, cables, sewers), creating separated, narrow tree pits instead of continuous planting strips (Hamano, 2009; Iizuka, 2009; Tan and Shibata, 2022). Karizumi (2010) noted that narrow space available for root growth has been widely recognized as the crucial issue for long-term street tree growing in Japan. With the spreading of the tree roots in the restricted planting pits, most of the soil will become consolidated; consequently, tree root growth will cause pavement and sidewalk upheaval. According to Ground Maintenance Manual in Landscape Planting, soil penetrometer measurements have been used extensively to quantify the vertical distribution of soil hardness in Japan (Research Committee of Japanese Institute of Landscape Architecture, 2000). Previous research has demonstrated soil hardness as a quantitative predictor of tree vitality. For instance, Ohnuki and Matsumoto (1992) examined the soil compaction caused by the anthropogenic trampling is in relation to impeding the soil gas exchange and the rainwater penetration. Kume and Hioki (2006) indicated that soil hardness (the layer of 10-20cm) significantly affected the tree vitality of *Prunus yedoensis* planted in the block park. Based on the boring investigation data, the study of Seko et al., 2017 found that soil hardness (the layer of 1.5 m) significantly correlated to tree root uplifting. However, there is very little work has been conducted to assess soil quality within the roadside in Japan, whereas soil hardness constraints often alert tree managers, local information on soil physical and chemical limitations are often neglected.

The main purpose of this chapter was to throw light on the significantly neglected research aspect of soil properties limitation on tree performance in Japan by the focus on Kyoto City. Attempts to understand the soil quality of streetscape soils in Kyoto City, with an emphasis on evaluating specific soil properties limitation on the street tree condition, through the empirical data and laboratory analysis. Therefore, this chapter includes two objectives: 1) to investigate the characteristics of soil in the center streetscape of Kyoto City, 2) to assess the soil properties correlated to street trees condition in Kyoto City's streetscape, this research was not intended to be a comprehensive survey of street tree landscapes of Kyoto City but hope to contribute to the baseline finding which can provide practical hints on soil management.

3.2. Materials and methods

3.2.1. Study site

Kyoto City, the capital of Kyoto Prefecture, is located in a basin and experiences a humid subtropical climate with hot, wet summers (June–August) and cold, dry winters (December–February). The mean annual temperature is 15.9℃, and the annual precipitation of 1491.3mm (Japan Meteorological Agency, 2019).

The Kyoto Basin is made up of alluvial fans by the Katsura River and Kamo River. There is remaining a lot of gravel soil in urban areas and partly existing clay layer as sediment from the ancient sea/lake era. In particular, the marine clay, as one type of sediment from the ancient sea era in the Kyoto Basin, which contains the strongly acidic sulfur component has to inhibit the growth of plants. Generally, Japanese soil is considered highly acidic, and many tree species have evolved to be acid resistant. In Kyoto City, the soil pH test will be conducted before using as the roadside soil, to avoiding strong acidity/alkalinity soil is not suitable for urban greening growth (Kyoto Urban Greening Manual, 2004).

3.2.2. Target species

The species of interest was the top one common street tree species in Kyoto City, *Ginkgo biloba* (35% of the total population of all street trees in Kyoto City). *G. biloba* also ranking the most widely used species of street tree throughout Japan. Iizuka and Funakubo (2019) reported that *G. biloba* accounts for 8% of all street tree species in Japan.

According to Karizumi (1979), the tree root system of *G. biloba* was described as: medium to large diameter tap and oblique roots system; Vertical distribution is deep tap root with sinker roots growth, and horizontally spreading medium diameter of lateral roots; Dense fine root growth; Alkaline/Acid pH resistance (see Appendix 13)

3.2.3. Data collection

Sample location

According to Kume and Hioki (2006), for many tree species, the required growth range of the root system is in a circle with a radius of 2 to 6 times the diameter above root crown (DRC) (grey circle in Fig 3.1A). In Kyoto city, there are three standard scenarios of the tree planting type: (a) tree pit: standard length of 1.5m with varying width (<=1.5m), (b) tree pit: standard length of 1.8m with varying width (<=1.8m), (c) planting strip: standard width of 1.5m with varying length (>=2.5m). In our study, to avoid the impact on the root growth due to the soil penetration experiment and aim to identify the soil variables that influence tree health under the same planting condition, the planting strip type with sufficient measurement space was selected as a control condition.

Five major roads planted with *G. biloba* that runs through the center of the urban area were chosen as the study sites (Fig 3.1B). On each road, 6 street trees of *G. biloba* were randomly selected as the sample trees. These 5 roads include commercial, education & institution, residential, open space (i.e., park) adjacent land use.

Soil sampling

A soil sampling of 30 street trees in five streets was conducted from June to July 2020. For each sample tree, the soil sampling was conducted in a circle with a radius of 4 times the diameter above root crown (DRC) (red circle in Fig 3.1A). Three 100-cc (Ø 50×51 mm) soil core ring was used for undisturbed soil sampling from 1-6cm depth (the grass cover of 0-1cm was removed) to help clarify the saturated hydraulic conductivity (a total of 90 sample core ring samples), and 150g of soil was taken as disturbed samples from three points for clarifying the soil properties experiment (red points in Fig 3.1A).

SH Penetrometer Experiment & gas concentration measurement

Two points of the SH Penetrometer Experiment have been conducted to measure the vertical distribution of soil hardness (yellow points in Fig 3.1A). The SH Penetrometer Experiment was using a cone penetrometer equipped with a metal cone on top and a 3kg weight to push the cone penetrating soils (Fig 3.2A). The Datalogger was used to record each one drop penetrability (ODP cm/drop) until arriving at the depth of 60cm. Gas concentration measurement was using the gas sensor device (CO_2 monitor: COZY-1, oxygen concentration meter: OXY-1-M; Ichinenjiko Co., Ltd, Japan) (Fig 3.2B). A gas sampling pipe (Fig 3.2C) connected with the gas sensor device was buried in the hole excavated by the SH Penetrometer Experiment, and the value of the concentration of CO_2 and O_2 were recorded after 60 seconds.

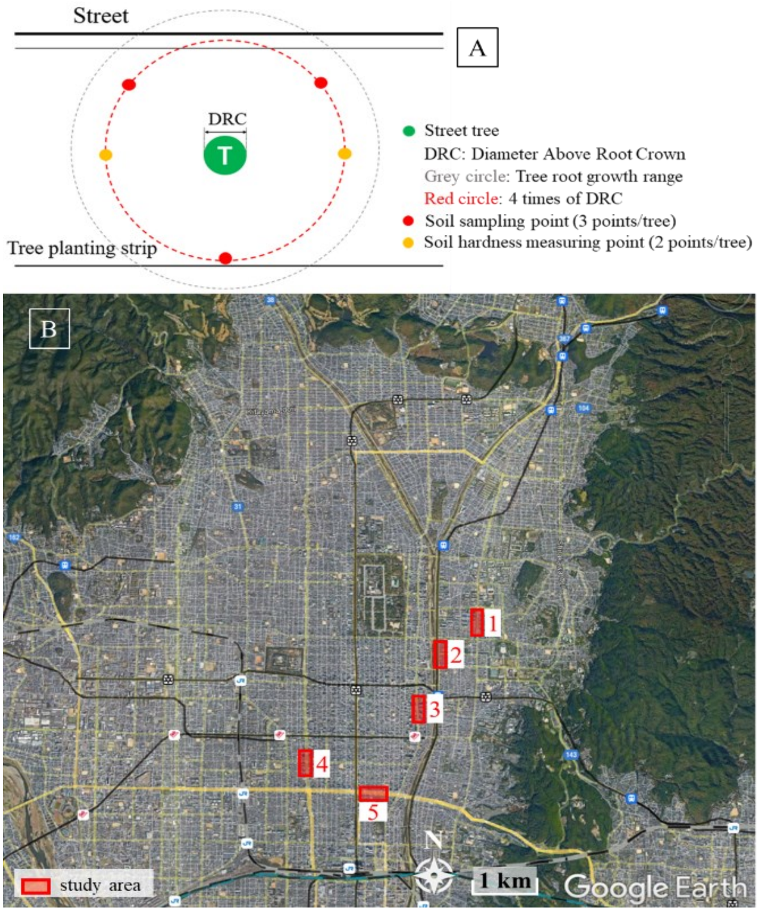


Figure 3. 1 Soil sampling protocol (A) and the research sites in Kyoto City (B). Sites: 1-Higashioji-Dori (HO); 2-Kawabata-Dori (KB); 3-Kawaramachi-Dori (KR); 4-Horikawa-Dori (HK); 5-Gojo-Dori (G)

Figure 3. 2 The SH Penetrometer Experiment and gas concentration measurement, (A) a cone penetrometer equipped with a 3kg weight to push the cone penetrating soils and datalogger was used to record each one drop penetrability (ODP cm/drop) (***source***: Daito Techno Green Co., Ltd); (B) Gas concentration sensor device (***source***: Author); (C) A gas sampling pipe connected with the gas sensor (***source***: Yuki Kato).

Tree attributes

The tree decline rating method was adopted to assess the tree health condition (Hori, 2014; Tan and Shibata, 2022). The eleven parameters including tree vigor, density of branches and foliage, leaf color, damage of lower crown, damage or decay of tree bark, leaf (bud) size, damage of upper crown, tree base condition, bark metabolism, branch extension amount, and presence or absence of trunk body sprout and basal shoot were evaluated in the rating form (Appendix 2). Each parameter had five-level evaluation criteria, from 0 (best) to 4 (worst). One person did all tree condition ratings by observation from the ground level of several directions. The formulae used in the calculations was:

$$H = (1 - \frac{\sum_{i=1}^{11} hi}{44}) \times 100 \quad (1)$$

where *hi* is the rating of each item and *H* is the tree health score. The health condition of trees was classified into five categories based on the tree health score: excellent (100–94), good (93–89), fair (88–80), poor (79–65), and dying (≤64).

3.2.4. Soil data analysis

Soil properties

The 150g disturbed soil samples were air-dried in the laboratory and ground to including grinding to pass a 2mm sieve for the physical and chemical test. The undisturbed samples were used to determine the hydraulic conductivity. The physical and chemical attributes had been assessed with the following selected standard methods: (1) particle-size distribution and texture analysis, the organic matter of the soil samples was removed using H_2O_2, then the sample was ultrasonicated. Sand content (0.05-2.0mm diameter) was determined by the sieving method, and silt content (0.002-0.05mm diameter) was determined using sieving method with the pipette method. The clay content (<0.002 mm) was determined by the pipette method (Gee and Or, 2002); (2) pH (sample to water ratio of 1:5) was measured with a Benchtop pH meter (F-70 Series, Horiba, Kyoto, Japan); (3) soil saturated hydraulic conductivity was calculated using the formulae (DIK-4012, Daiki Rika Kogyo Co., Ltd, Japan):

$$K = \frac{Q}{At\Delta H/L} \text{ (cm/sec)} \quad (2)$$

Where, K means soil saturated hydraulic conductivity(cm/s), Q means water volume (ml), A means the cross-section area of the core sample (19.6cm^2), t means time (s), ΔH means potential difference (6.8cm), and L means the sample thickness (5.1cm).

Soil hardness

To identify specific soil layers that affect tree vitality, the soil hardness measurement data of 60cm depth was divided into six groups. Each 10cm data as one group and the representative value (S) in each soil layer was calculated using the weighted average method, in accordance with the method used in previous work (Kume and Hioki, 2006). The larger value indicates the softer soil hardness. Table 3.1 showed an example of soil hardness measurement data, and the formula used to calculate the S(10-20cm) was:

$$S_{(10-20)} = \frac{ODP_5(a_5 - 10) + \sum_{n=6}^{12} ODP_n\ (a_n - a_{n-1}) + ODP_{13}(20 - a_{12})}{10} \quad (3)$$

Where, n means the number, ODP_n means one drop penetrability (cm/drop), a_n means penetrate depths (cm).

Table 3. 1 An example of soil hardness measurement data

Number	ODP (cm/drop)	Penetrate depth(cm)
1	3.2	3.2
2	2.6	5.8
3	2.0	7.8
4	1.8	9.6
5	1.8	11.4
6	1.5	12.9
7	1.5	14.4
8	1.2	15.6
9	1.2	16.8
10	1.0	17.8
11	1.0	18.8
12	1.0	19.8
13	0.8	20.6
14	0.8	21.4

Statistical analysis

The normality in the data was checked with the Kolmogorov-Smirnov Test (α=0.05, P >0.05), and significance of association was assessed using the Pearson Correlation Coefficient. The correlation coefficients (Pearson) were classified as follows: r < 0.5 (weak correlation), 0.5 < r < 0.8 (medium correlation) and r > 0.8 (high correlation). To detect differences between the tree health between the two soil hardness groups, a *t*-test (two sample group assuming unequal variables) was used for testing the tree health condition between two (hard & soft) groups based on the soil hardness data. All the statistical analysis were conducted via SPSS Statistics version 19 (IBM Corp., NY, USA).

3.3. Results and Discussion

3.3.1. Tree attributes

The majority of *G.biloba* present good adaptability to the urban environment with very little damage planting in Kyoto City. The lowest recorded tree health condition score was 77.5, and the highest was 100. Trees in excellent condition accounted for the majority of those sampled (36.6%). In sampled trees, the same ratio of 26.7% could be classified as good and fair condition, and trees classified as poor and dying accounted for 10.0% and 0.0%, respectively (Table 3.2).

Table 3. 2 The health conditions of 30 sampled trees of *G.biloba* by five categories

	Excellent (100-94)	Good (93-89)	Fair (88-80)	Poor (79-65)	Dying (≤64)
n	11	8	8	3	0
%	36.6	26.7	26.7	10.0	0.0

3.3.2. Soil properties

Gravel ratio

The result of the gravel ratio given in Table 3.3, at a mean value of 14.89% (range from a minimum of 6.40% to a maximum of 31.10%), confirms the low contents of gravel or stones in soils. According to the evaluation criteria of soil analysis results (as standard for greening sites) (Research Committee of the Japanese Institute of Landscape Architecture, 2000), the gravel ratio was excellent. The excessive gravel/stone contents might be a concern for containing too many large buildings waste materials which impede tree root growth (Logsdon et at., 1987; Bridges, 1991). Compared to the high contents of gravel in Hong Kong (very stony with a mean 42.86%) (Jim, 1998a), in Kyoto City, the phase-out of recycled concrete stone usage has reduced the levels of gravel ratio in urban roadside soils (Kyoto Urban Greening Manual, 2004).

Soil texture & hydraulic conductivity (*K_S*)

The sampled soil texture indicated an extremely sand-textured which is dominated by sand at a mean of 75.02% (ranging from a minimum of 67.24% to a maximum of 82.48%. The silt and clay are minor fractions, with mean contents at 18.82% and 6.17%, respectively (Table 3.3). According to the USDA textural classification, on average, sampled soil textures were all determined to be in the categories of Loamy sand and Sandy loam (Fig.3.3). The ability of the soil to induce excessive permeability, aeration and workability can be enhanced by the high proportion of large sand particles because air and water can readily move through the large pore space (Harris et al., 1992; Jim 1998b; Hawver and Bassuk, 2007). Based on the evaluation criteria of soil analysis results (as standard for greening sites) (Research Committee of the Japanese Institute of Landscape Architecture, 2000) (see Table 3.4), the saturated hydraulic conductivities of sampled soil were good level. The characteristics of extremely sandy-textured soil might explain the excellent results of saturate hydraulic conductivity in our study, which found that the average saturate hydraulic conductivity of 8.81×10^{-3}. The high soil infiltration capacity, which was approximately 2-7 times better than that expected for a Loamy sand (4.05×10^{-3}cm/sec) and sandy loam (1.22×10^{-3}cm/sec) (Carsel and Parrish, 1988).

Table 3. 3 Statistical summary of selected soil properties of 90 streetscape soil samples in urban area Kyoto City

Attribute	Mean	S.D	Min.	Max.
Physical properties				
Gravel ratio (%)	14.89	±5.85	6.40	31.10
Sand (%)	75.02	±4.08	67.24	82.48
Silt (%)	18.82	±3.30	13.60	25.02
Clay (%)	6.17	±1.53	3.71	9.42
Hydraulic conductivity(cm/sec)	8.81×10^{-3}	$\pm6.21\times10^{-3}$	4.06×10^{-3}	2.28×10^{-2}
Chemical properties				
pH	6.54	±0.606	5.23	7.92

Table 3. 4 Evaluation criteria for soil analysis results for greening site, Research Committee of Japanese Institute of Landscape Architecture (2000)

	Excellent	Good	Bad	Very bad
Gravel ratio (%)	0-20	20-40	40-60	60<
Hydraulic conductivity(cm/sec)	10^{-2}	10^{-2}- 10^{-3}	10^{-3}- 10^{-4}	10^{-4}>
pH (H_20)	5.6-6.8	4.5-5.6; 6.8-8.0	3.5-4.5; 8.0-9.5	3.5>; 9.5<

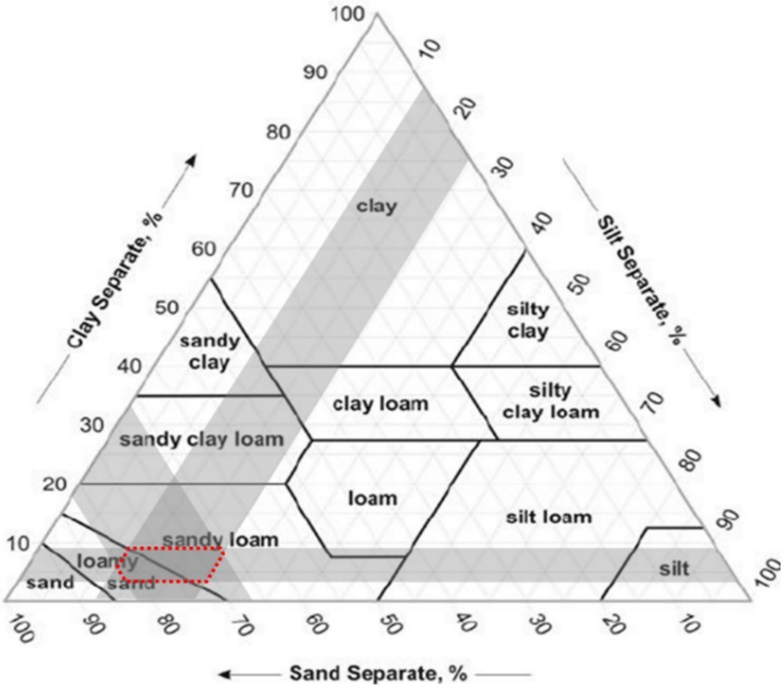


Figure 3. 3 The USDA soil classification with shaded area (red frame) encompassing the range of the textural classes in our studies.

Soil reaction (pH)

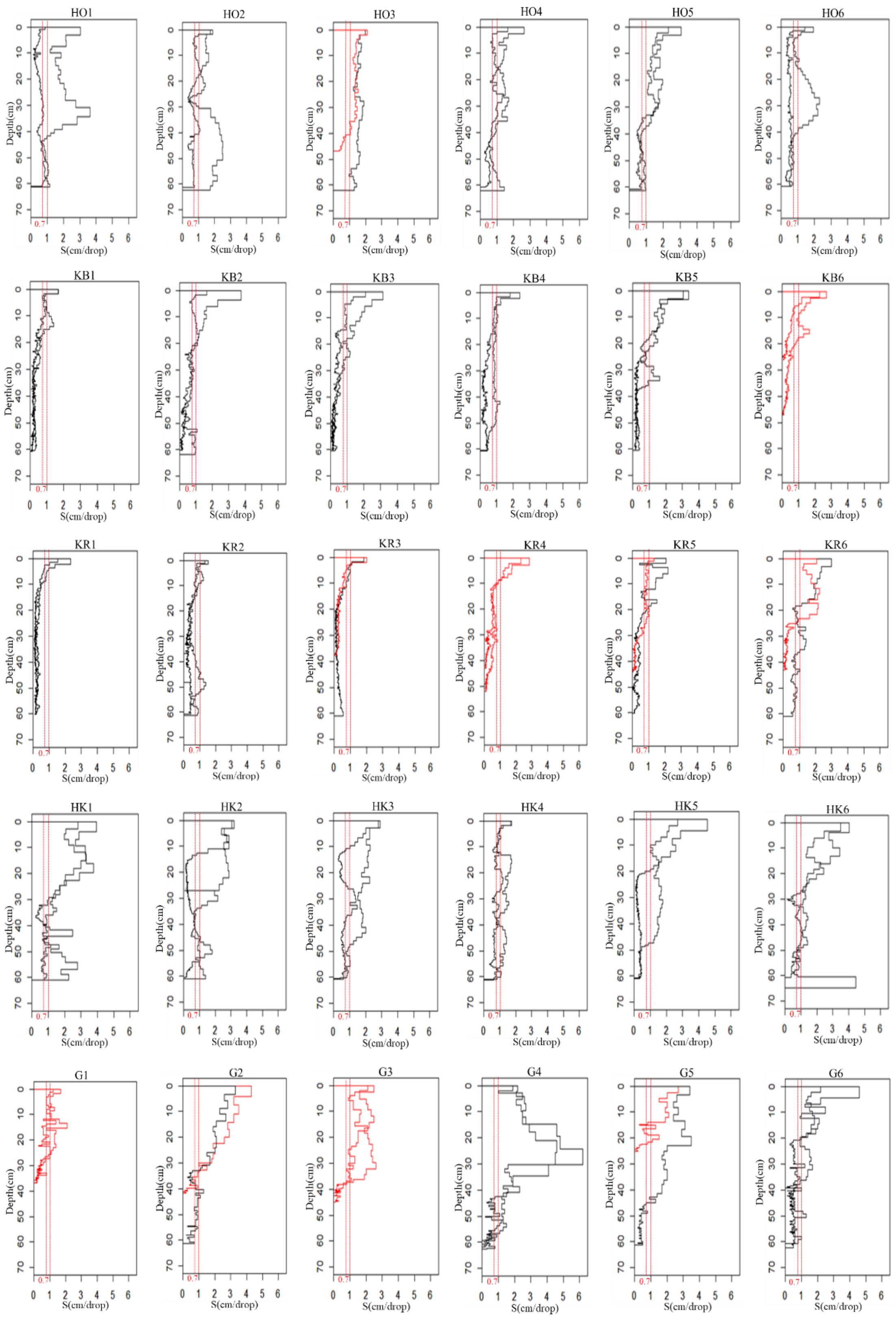
Soil pH influences urban street trees growth by many processes, including the solubility, availability and uptake of nutrient elements (Konijnendijk et al., 2005; Hawver and Bassuk, 2007). Previous research noted that the optimum pH for trees is approximately 5-7 because a near-neutral value favors the solubility of many nutrient elements and the activity of microorganisms (Hawver and Bassuk, 2007; Day and Dickinson 2008). Our result showed an excellent near-neutral soil pH of mean value 6.54 (minimum 5.23, maximum 7.92) (Table 3.3). Soils of urban tree sites generally tend to be more alkaline, especially in the city central region might be due to the dissolution of calcareous construction waste (e.g., concrete, cement) (Ware, 1990; Day and Dickinson, 2008; Ghosh et al., 2016). For example, soil pH value in Hong Kong was reported slightly to very strong alkaline (6.77 to 9.95) (Jim, 1998). Scharenbroch and Catania (2012) reported alkalinity in Chicago's suburban soils range from 7.1 to 8.2 and 6.6 to 8.3 in Kielce, Poland (Galuszka et al., 2011). A similar situation has also been observed in street tree soils in other studies in Japan, including Nagoya (mean pH7.12), Tokyo (52% of pH7-8), Sendai (53.3% of pH8-9) (Matsuda et al.,1981; Ozawa et al.,1975; Sato et al.,1974, 1975). For comparison, acidic soil is to be expected in humid subtropical environment like Japan and local hill and secondary forests (10-15cm) were measured to be at pH mean 5.03(±0.48) (Oyake et al., 2016) due to abundant rainfall. The results of optimum soil pH for street trees presented in our study could be connected with the fact that the stringent pH requirement for urban greenery planting in Kyoto City which stipulate that strong acidity or alkalinity soil should not use as a planting soil (Kyoto Urban Greening Manual, 2004)

3.3.3. Soil hardness

The results of soil hardness were expressed as in Fig. 3.4. In this study, the definition of soil hardness is classified using the evaluation criteria for soil hardness by Hasegawa penetration meter (Research Committee of the Japanese Institute of Landscape Architecture, 2000) (Table 3.5), which is very hard, (S) less than 0.7cm/drop; hard, (S) between 0.7 to 1.0 cm/drop; moderate, between 1.0 to 1.5 cm/drop; soft, between 1.5 to 4 cm/drop. Based on Fig. 3.4, our results demonstrated that soils hardness in KB, KR street are extremely compact than HO, HK and G street as almost every sample street appear to have continuous over 10cm soil layer of (S) value is below 0.7cm/drop which will impact the tree roots growth. However, we could not conclude the reason why the KB, KR street showed comparative compact soil condition here. Further investigation therefore needed to clarify this difference. In G street, the soil layer was soft until the depth of about 40cm; after 40cm depth, the soil resistance suddenly increased, and some failed (e.g., G1, G2, G3, G5) to penetrate likely due to the presence of hard laterite pan or stone layer. Koshimizu et al., (1979) and Masuda et al., (1983) suggested that the impact of trampling on soil hardness mainly affects the depth range approximately of 10-20cm. Our results do not reflect the obvious soil hardness that occurred at the layer of 10-20cm, indicating that relatively little external compressive force such as vehicular traffic or human trampling induces soil compaction.

Table 3. 5 Evaluation criteria for soil hardness by Hasegawa penetration meter, Research Committee of the Japanese Institute of Landscape Architecture, 2000

(S) cm/drop	Hardness level	Roots penetrability
0.7 >	very hard	Difficult to extend for majority roots
0.7 - 1.0	hard	Restriction on root extension
1.0 - 1.5	moderate	Restriction on root extension for some
1.5 - 4.0	soft	No restriction
4.0 <	very soft	//



Note: not complete (impenetrable down to 60cm) measurement used in red line because of the presence of hard laterite pan or stone layer

Figure 3. 4 The pattern of 30 sample street trees soil hardness (total 60 sampling points, 2points/tree) in five streets of Kyoto City; Horizontal axis (S) represents the penetrating depth(cm) per one drop of the weight and vertical axis represents the cumulative depth (cm).

3.3.4. Soil gas aeration

Soil aeration refers to the exchange of oxygen and carbon dioxide, which occurs between the soil and atmosphere (Hawver and Bassuk, 2007). The poor aeration caused by soil compaction influence tree root respiration, diminished water and mineral uptake, resulting in poor tree growth (Hawver and Bassuk, 2007; Kämäräinen et al., 2018). A concentration of less than 10% oxygen in the soil atmosphere is generally considered inadequate for healthy root growth, and oxygen contents of 16% or more will guarantee good root growth (Konijnendijk et al., 2005; Kämäräinen et al., 2018). Our results presented a favorable soil aeration of O_2 concentration with approximately 17%-21% (Table 3.6), which is attributed to the loamy sand and sandy loam texture in our case often exhibit favorable aeration because air and water can readily move though the large pore spaces (Hawver and Bassuk, 2007). However, as previous studies pointed out, soil respiration is associated with many factors such as abiotic factors and microbial activities (Konijnendijk et al., 2005; Kim and Yoo, 2021). Therefore, further research is needed to investigate the effects of other environmental factors on the air composition in soil aeration.

Table 3. 6 The average CO_2&O_2 (mol%) gas concentration of 26 valid sample trees (Four sample trees data was failed to collect due to the impenetrable down to 60cm).

	CO_2	**O_2**		**CO_2**	**O_2**
HO1	0.27	20.10	KR3*	0.56	20.10
HO2	0.49	19.45	KR5*	0.55	20.90
HO3*	0.56	19.45	KR6*	0.58	18.95
HO4	0.36	19.95	HK1	0.74	18.40
HO5	0.26	20.35	HK2	0.51	19.25
HO6	0.31	20.25	HK3	1.06	17.80
KB1	0.48	19.85	HK4	0.34	20.40
KB2	0.51	19.35	HK5	0.90	19.50
KB3	0.80	19.45	HK6	0.18	20.10
KB4	0.61	20.10	G2	0.20	19.60
KB5	0.66	19.85	G4	0.99	18.55
KR1	0.66	20.20	G5*	0.34	18.30
KR2	0.67	19.20	G6	0.50	18.18

*denote only one point data, the rest of data is the average of two points

3.3.5. Soil properties correlation with tree attributes

Of all soil properties, only the soil hardness of layer 50-60cm was found to be a significantly positive correlation with tree health (r = 0.557; p = 0.003) (Table 3.7). This may be explained by the fact that the soil compaction that happened in the deep layer will hinder the growth of the medium, large diameter, and deep extension root system (like *Ginkgo biloba*), and further affect the tree vitality. Kume and Hioki, (2006) found that the soil compaction that happened at a depth of 10 to 30 cm impede the root system growth of *Prunus* ×*yedoensis* planting in the block parks, especially the soil consolidated of layers from 10 to 20 cm. Because the root system of *Prunus* ×*yedoensis* is centrally distributed at the depth of 10-40cm. Based on the total 60 soil hardness experiment taken from 30 street trees, we can observe that almost every sample tree had at least one soil experiment, below the depth of 50cm, appeared to have acute compaction that continuously penetration below 0.7cm/drop. In addition, compared to *Prunus ×yedoensis*, the deep vertical distribution root type of *Ginkgo biloba* may be more vulnerable to be affected by the soil consolidation from the deep soil layer.

Other properties, like texture, hydraulic conductivity, and soil reaction (pH) were unexpectedly not correlated with any tree attributes. Our data did not follow the same trend reported by previous other studies conducted in Hong Kong, Chicago, and Latvia which predicted the soil properties tightly linked to tree attributes (Jim, 1998a, b; Scharenbroch and Catania, 2012; Cekestere and Osvalde, 2013). In comparison, our research supports the similar observations found in the Singapore case study (Ghosh et al., 2016) which highlighted the soil characteristics were poor predictors to urban tree performance. The possible reasons that our data performed poorly predicting street tree attributes in Kyoto City can be listed as follows: a) overall, the majority of *Ginkgo biloba* behave well in Kyoto City. The previous research by Tan and Shibata (2022) revealed that *Ginkgo biloba* as the common street tree species in Kyoto City, showing good adaptability to the restricted planting conditions. b) relatively homogeneous and high soil physical and chemical properties in Kyoto city streetscape for the street trees growth. Likely, the soil properties were more tightly linked to tree attributes in these studies (Scharenbroch and Catania, 2012; Cekestere and Osvalde, 2013) due to the soil in Chicago and Riga, Latvia were generally poor in quality. c) we surmise that above-ground anthropogenic management practice (e.g., pruning, narrow tree pit size) has much more significantly influence on tree health compare the soil part. Peper et al., 2001 purposed that pruning has a significant impact on tree size and leaf area, potentially more than climate and soil characteristics.

Table 3. 7 Pearson's correlation coefficients between the tree health and soil properties

Variable (y)	**Tree Health**	
	r value	*P*-value
Physical properties		
Gravel ratio (%)	-0.239	0.204
Sand (%)	0.312	0.093
Silt (%)	-0.323	0.082
Clay (%)	-0.138	0.469
Hydraulic conductivity(cm/sec)	0.081	0.669
Chemical properties		
pH (H_20)	-0.306	0.101
Soil hardness		
Layer 0-10cm	0.084	0.660
Layer 10-20cm	-0.088	0.642
Layer 20-30cm	-0.084	0.657
Layer 30-40cm	-0.135	0.484
Layer 40-50cm	0.129	0.512
Layer 50-60cm	0.557	0.003**

** denote significance at the 0.001 probability level.

3.3.6. Research limitation

Though there are various limitations to this study, the results give a fundamental understanding of the soil environment for street trees in Kyoto City. Limitations of the analysis include：a) limitations associated with tree condition assessment. The tree health quantitative metric needs a more precise and objective assessment, not only based on the crude ocular observation method. Such as many previous studies (Kume and Hioki, 2006; Scharenbroch and Catania, 2012; Ghosh et al., 2016; Kim and Yoo, 2021) conducted the tree investigation on leaf chlorophyll content (leaf greenness) to determine the tree vitality. b) the soil samples taken from different soil layers should be considered. For instance, the existing soil layer (20-30cm depth) could provide more comprehensive soil information. c) a limited number of samples and samples collecting area. The geographic range and tree species need to be expanded upon to see if soil properties will predict urban tree performance more broadly than has been tested in the current study. Such as only one common street tree species has been selected as our research target, and we did not collect data from industrial land use. Moreover, this study was limited by the choice of planting strip sites, more comprehensive coverage of single tree pit type should be implemented in the next stage of the study. d) measurement of more soil parameters (e.g., bulk density, organic matter, nutrients, cation-exchange capacity) should be included for soil experiment which will likely contribute to urban soil quality in relation to tree performance.

3.4 Conclusion

The qualities limitations of urban soil can undermine the growth rate, health vigor, and long-term welfare of street trees. Soil properties assessment is necessary and helpful to landscapers working with compacted site conditions. This research was conducted to evaluate the influence of soil physical, chemical, and hardness properties on Kyoto's street trees. Our study provides evidence that relatively homogeneous streetscape soils in Kyoto City and well-suited for tree growing. The results also identified that soil hardness (50-60 layers) depth might be most strongly influence the tree attributes (*Ginkgo biloba* Linn.). Future studies should apply more comprehensive soil variables system to a broader area and other species to confirm their predictive capabilities for street tree performance.

3.5. Reference

Bridges, E. M., 1991. Waste materials in urban soils. Soils in the urban environment., 28-46.

Carsel, R. F., Parrish, R. S., 1988. Developing joint probability distributions of soil water retention characteristics. Water resources research, 24(5), 755-769.

Cekstere, G., Osvalde, A., 2013. A study of chemical characteristics of soil in relation to street trees status in Riga (Latvia). Urban Forestry & Urban Greening, 12(1), 69-78.

Craul, P. J., 1985. A description of urban soils and their desired characteristics. Journal of arboriculture, 11(11), 330-339.

Craul, P. J., 1992. Urban soil in landscape design. John Wiley & Sons.

Daiki Rika Kogyo Co., Ltd. 2004 Permeability measuring instrument DIK-4012.

https://www.daiki.co.jp/wp/wp-content/uploads/2021/03/4012.pdf (In Japanese) (Accessed on 31/12/2021).

Day, S. D., Bassuk, N. L., 1994. A review of the effects of soil compaction and amelioration treatments on landscape trees. Journal of arboriculture, 20(1), 9-17.

Day, S. D., Dickinson, S. B., 2008. Managing stormwater for urban sustainability using trees and structural soils. Virginia Polytechnic Institute and State University, Blacksburg, VA, 63.

Dover, J. W. 2015. Green infrastructure: incorporating plants and enhancing biodiversity in buildings and urban environments. Routledge.

Gałuszka, A., Migaszewski, Z. M., Podlaski, R., Dołęgowska, S., Michalik, A., 2011. The influence of chloride deicers on mineral nutrition and the health status of roadside trees in the city of Kielce, Poland. Environmental Monitoring and Assessment, 176(1), 451-464.

Gee, G. W., Or D., 2002. 2.4 Particle-size analysis. Methods of soil analysis. Part, 4(598), 255-293.

Ghosh, S., Scharenbroch, B. C., Ow, L. F., 2016. Soil organic carbon distribution in roadside soils of Singapore. Chemosphere, 165, 163-172.

Haaland, C., van Den Bosch, C. K., 2015. Challenges and strategies for urban green-space planning in cities undergoing densification: A review. Urban forestry & urban greening, 14(4), 760-771.

Hamano, C., 2009. Subject for draw up a repair precept of street trees. Journal of the Japanese Society of Revegetation Technology 35, 259–261 (In Japanese).

Harris, R. W., Clark, J. R., Matheny, N. P. 2004. Arboriculture: Integrated management of landscape trees, shrubs, and vines 4th ed Prentice Hall Upper Saddle River.

Hawver, G. A., Bassuk, N. L. 2007. Soils: The key to successful establishment of urban vegetation. In Urban and Community Forestry in the Northeast (pp. 165-182). Springer, Dordrecht.

Hori, T., 2014. Diagonosis Method of Tree Health. Kodansha Ltd, Tokyo (In Japanese).

HORIBA, Ltd. 2021. Benchtop pH meter F-70 Series https://www.horiba.com/uploads/media/HRA1169G_01.pdf (In Japanese) (Accessed on 31/12/2021).

Iizuka, Y., 2009. Current status of the root system and the planting bases of street trees. Journal of the Japanese Society of Revegetation Technology 35(2), 262-266 (In Japanese).

Iizuka, Y., 2018. Improvement of safety and amenity of street trees. Journal of the Japanese Society of Revegetation Technology 44, 297–301 (In Japanese).

Iizuka, Y., Funakubo, S., 2019. Current status and changes of street trees. Tree and Forest Health 23-2:110-111 (In Japanese).

Iizuka,Y., Funakubo S., 2018. The roadside tree of Japan VIII, Technical Note of National Institute for Land and infrastructure Management. National Institute for Land and infrastructure Management Ministry of Land, Infrastructure, Transport and Tourism, Japan (In Japanese, with English synopsis).

Japan Meteorological Agency, 2019. Normal Value (Value for Each Year/ Month) of Meteorological Data (In Japanese) Retrieved from https://www.data.jma.go.jp/obd/stats/etrn/view/annually_s.php?prec_no=61&block_no=47759&year=&month=&day=&view= (Accessed on 01/20/2020).

Jim, C. Y., 1998a. Physical and chemical properties of a Hong Kong roadside soil in relation to urban tree growth. Urban Ecosystems, 2(2), 171-181.

Jim, C. Y., 1998b. Urban soil characteristics and limitations for landscape planting in Hong Kong. Landscape and urban planning, 40(4), 235-249.

Jim, C. Y., Konijnendijk van den Bosch, C., Chen, W. Y., 2018. Acute challenges and solutions for urban forestry in compact and densifying cities. Journal of Urban Planning and Development, 144(3), 04018025.

Jim, C. Y., 2019. Soil volume restrictions and urban soil design for trees in confined planting sites. Journal of Landscape Architecture, 14(1), 84-91.

Karizumi, N., 1979. Illustrations of Tree Roots. Seibundo Shinkosha Publ. Co., Tokyo (In Japanese).

Karizumi, N., 2010. The Latest Illustrations of Tree Roots. Seibundo Shinkosha Publ. Co., Tokyo (In Japanese)

Kim, Y. J., Yoo, G., 2021. Suggested key variables for assessment of soil quality in urban roadside tree systems. Journal of Soils and Sediments, 21(5), 2130-2140.

Konijnendijk, C. C., Nilsson, K., Randrup, T. B., Schipperijn, J. (Eds.)., 2005. Urban forests and trees: a reference book. Springer Science & Business Media.

Koshimizu, H., Iizuka, K., Fujisaki, K., 1979. Wear injury of Manilagrass (Zoysia matrella Merr.) produced by pedestrian traffic. Journal of Japanese Society of Turfgrass Science 8(1), 41-47 (In Japanese).

Kyoto Urban Greening Manual, 2004. Kyoto City Construction Bureau (In Japanese).

Kume, M., Hioki, Y., 2006. Relationships between vitality of Prunus yedoensis Matsum. and soil hardness in block parks. Japanese Society of Revegetation Technology 32(1), 98-101 (In Japanese).

Kämäräinen, A. S., Riikonen, A., Simojoki, A., Lindén, L., 2018. A Case Study of Street Tree Soil Aeration in Two Different Soil Types. Arboriculture & Urban Forestry, 44(4).

Logsdon, S. D., Parker, J. C., Reneau, R. B., 1987. Root growth as influenced by aggregate size. Plant and Soil, 99(2), 267-275.

Masuda, T., Furuie, T., Yoshida, S., 1983. The influence of Trampling on the growth of <I> Ophiopogon Japonicus </I>. Journal of Japanese Institute of Landscape Architecture 47(5), 117-122 (In Japanese).

Matsuda. T., Morimoto, Y., Hasegawa, S., 1981. Soil properties and growth conditions of street trees – a case study in Nagoya City -. Journal of Japanese Institute of Landscape Architecture 44(3): 155-160 (In Japanese).

Mullaney, J., Lucke, T., Trueman, S. J., 2015. A review of benefits and challenges in growing street trees in paved urban environments. Landscape and Urban Planning, 134, 157-166.

Ohnuki, N., Matsumoto S., 1992. Basic studies on soil environment for sound growth of street trees. Journal of Japanese Institute of Landscape Architecture 56(1):39-44 (In Japanese).

Oyake, Y., Imanishi, J., Yoshida, H., Shibata, S., 2016. Analysis on vegetation and soil after 18-19 years of planting at an Osaka-group cut slope in Kizugawa City, Kyoto, Japan. Japanese Society of Revegetation Technology, 42(2), 308-319.

Ozawa, T., Kawakami, T., Kitazawa, K., Hagiwara, N., Kondo, M., Ichimura, M., 1975. Fundamental studies on the mode of life of street trees – effect of the state of soil on the growth of street trees -. Journal of Japanese Institute of Landscape Architecture 39(1), 23-34 (In Japanese).

Patterson, J. C. 1977., Soil compaction--effects on urban vegetation. Journal of Arboriculture.

Patterson, J. C., Murray, J., Short, J., 1980. The impact of urban soils on vegetation. In: Third Conference of the Metropolitan Tree Improve. Alliance, Piscataway. pp. 33-56.

Peper, P. J., McPherson, E. G., Mori, S. M., 2001. Equations for predicting diameter, height, crown width, and leaf area of San Joaquin Valley street trees. journal of Arboriculture, 27(6), 306-317.

Research Committee of the Japanese Institute of Landscape Architecture, 2000. Ground maintenance manual for landscape planting. Journal of Japanese Institute of Landscape Architecture 63(3):224-

241
Sato, K., Yamane, Y., 1974. About street tree (*Zelkova serrata*) soil. Street trees protection comprehensive survey report 36-43 (In Japanese).
Sato, K., Yamane, Y., 1975. About street tree (*Zelkova serrata*) soil (Second Part). Street trees protection comprehensive survey report 33-42 (In Japanese).
Seko, S., Fukui, W., 2017. The Relationship between the Incidence of the Pavement/Curb Failure by Street Tree Roots and Soil Conditions of Boring Investigation Data in Urban Area of Kyoto City. Journal of Japanese Institute of Landscape Architecture 10(0), 119-124 (In Japanese).
Scharenbroch, B. C., Carter, D., Bialecki, M., Fahey, R., Scheberl, L., Catania, M., Raciti, S., 2017. A rapid urban site index for assessing the quality of street tree planting sites. Urban Forestry & Urban Greening, 27, 279-286.
Scharenbroch, B. C., Catania, M., 2012. Soil quality attributes as indicators of urban tree performance. Arboriculture & Urban Forestry, 38(5), 214-228.
Short, J. R., Fanning, D. S., McIntosh, M. S., Foss, J. E., Patterson, J. C., 1986. Soils of the Mall in Washington, DC: I. Statistical summary of properties. Soil Science Society of America Journal, 50(3), 699-705.
Schoenholtz, S. H., Van Miegroet, H., Burger, J. A., 2000. A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. Forest ecology and management, 138(1-3), 335-356.
Tan, X., Shibata, S., 2022. Factors influencing street tree health in constrained planting spaces: evidence from Kyoto City, Japan. Urban Forestry & Urban Greening, 127416.
Udawatta, R. P., Henderson, G. S., 2003. Root distribution relationships to soil properties in Missouri oak stands: A productivity index approach. Soil Science Society of America Journal, 67(6), 1869-1878.
Ware, G., 1990. Constraints to tree growth imposed by urban soil alkalinity. Journal of Arboriculture, 16(2), 35-38.

4. Estimation of ecosystem services provided by street trees in Kyoto City

4.1. Introduction

Urbanization, one of the most transformative trends in the 21st century, is accompanied by increasing populations and socio-economic activities concentrated in cities. In recent decades, urbanization adversely impacts urban ecosystems and environmental quality through phenomena such as the urban heat island effect, air pollution, and alterations to hydrological systems (Roy et at., 2012; Li et al., 2017). Since the publication of the Millennium Ecosystem Assessment (MA) (MA, 2005) and The Economics of Ecosystems and Biodiversity (TEEB) report (Kumar, 2012), ecosystem services have gained broader attention in many parts of the world (Lin et al., 2019; Raum et al., 2012). Ecosystem services (hereafter referred to as ES) refer to the life-support functions performed by natural ecosystems that underpin humanity's most fundamental sources of well-being (Daily, 1997). The strong desire to develop a sustainable urban environment that delivers the ES has encouraged policymakers and scholars to direct their attention to evaluating the potential of urban trees to mitigate environmental degradation (Roy et at., 2012).

Street trees are recognized as integral components of urban ecosystems, which can improve environmental quality by providing significant ecological benefits (Dover, 2015). There is a growing body of literature that highlights the ES provided by street trees, such as storing carbon (McPherson and Simpson,1999; Nowak and Crane, 2002), regulating the air quality (Nowak et al., 2006), as well as improving the streetscape and amenity (Dover, 2015; Jim and Chen, 2006). Street trees also appear to be a feasible option for ameliorating the urban heat-island effect (Rahman et al., 2017; Rahman et al., 2020a; 2020b). Moreover, trees play an important role in urban catchment hydrology through canopy interception and soil infiltration of rainfall (Livesley et al., 2014; Rahman et al., 2019).

Despite the high level of scholarly recognition of street tree benefits, many local governments fail to recognize the importance of street trees due to unknown economic values, while the costs of damage by trees such as leaf litter and infrastructure damage are widely reported (Dover, 2015; Mullaney et al., 2015). Evidence of the economic worth of street trees in monetary terms is essential for decision-makers as it offers baseline information for long-term street-tree management and maintenance practices (Rogers et al., 2015). To understand the potential ES more fully and maximize the benefits of urban trees, several urban forest models have been developed and implemented in different cities (Lin et al., 2019; Rötzer et al., 2020). The most frequently used model is the i-Tree software developed by the U.S. Forest Service (www. itreetools.org), which provides a methodology using field data to assess the biophysical state and economic value of urban and community forests. Many studies based on the i-Tree software have demonstrated that the monetary values of ecosystem benefits provided by street trees exceed the annual cost of tree management. A study conducted in New York and Indianapolis showed that every $1 spent per year on tree-care-related expenditure resulted in US$5.6 and US$6.09 worth of ecosystem benefits, respectively, which was a greater economic benefit than that reported from any other city to date (Peper et al., 2007; Peper et al., 2008).

Although i-Tree tools have been extensively used across the US and European countries over the past 10 years, limited research using this method has been conducted in other parts of the world (Roy et at., 2012). There are still uncertainties in applying US-based ES and associated benefit quantification models to other countries without appropriate modifications. For example, the fact that the acquisition of site-specific parameters is unavailable or insufficient will indicate possible inaccuracies of the results (Jim and Chen, 2009; Lin et al., 2019). To improve model functionality in other countries, Hirabayashi et al., 2016 and 2019 conducted pilot studies in Japan, in which the accuracy of analysis results was enhanced by largely customizing the models and their parameters.

This chapter describes the application of i-Tree Eco with customized models and parameters for monetarization of the street tree benefits in Kyoto, Japan. The objectives of this chapter were as follows: (1). To demonstrate the procedure for implementing the i-Tree Eco project in Japan, including collecting all relevant data sources and explaining customizations conducted for each model. (2). To present objective data on the value of ecosystem services provided by street trees in Kyoto city as baseline data for evaluating returns on tree management investment. (3). To appeal for a better understanding of street trees as green assets, which could help ensure adequate tree maintenance and lead to future improvements in management and plans.

4.2. Materials and methods

4.2.1. The City of Kyoto

Kyoto City, the capital of Kyoto Prefecture, is located in the central part of Honshu, Japan (Figure 4.1), which has a humid subtropical climate with hot, humid summers (June–August), and cold, dry winters (December–February). Due to its basin topography, Kyoto experiences the most severe summer heat in Japan, with a mean daily maximum temperature of around 37 °C in August (Japan Meteorological Agency, 2019). In the central urban area of Kyoto City, given the limited large green spaces, street trees are recognized as an irreplaceable green infrastructure for mitigating urban heat island effects and providing critical ecological connectivity to promote faunal abundance and diversity (Kyoto City Office, 2010).

4.2.2. Collecting tree data

With reference to the basic plan for greening of Kyoto City, the green corridor zone was selected as the research area, which embraces the east to west extent from Shirakawa-Dori Street to Nishioji-Dori Street and stretches north to south from Kitayama-Dori Street to Jyujo-Dori Street (Kyoto City Office, 2010). The total area is 48.85 km^2, covering seven wards with a total population of 451,462(Ministry of Internal Affairs and Communications, 2018). Field sampling of 1230 street trees was conducted from June to October 2018. Approximately 10% of street trees on the 41 streets were sampled at equal distances to generate the tree inventory (Figure 4.1). Field measurements were performed in accordance with the i-Tree Eco field manual (US Forest Service, 2020). Tree species and adjacent land use were verified in the field. Health condition, crown light exposure, and percent crown missing were estimated by one person by visual inspection. Total tree height, height to crown base, diameter at breast height (DBH), crown width was measured using a Trupulse 360 laser rangefinder (Laser Technology, Inc., CO, USA) and a diameter tape.

4.2.3. Estimation of ecosystem services by i-Tree Eco

i-Tree Eco estimates urban and community forest features such as biomass and leaf area and then, based on these properties, quantifies the ES provided by the forests. The system comprises of three components: model codes written in computer languages, parameters for the models (e.g., coefficients in model equations), and input data (e.g., weather data).

Currently, for a total of about 40 countries officially supported, input data such as tree species, weather, upper air, air quality, and location-related data (such as coordinates and population) are stored in the i-Tree server computers. Using these data, the analyses can be conducted in these 40 countries, with only the tree data prepared by users. Because the species, weather, and upper-air

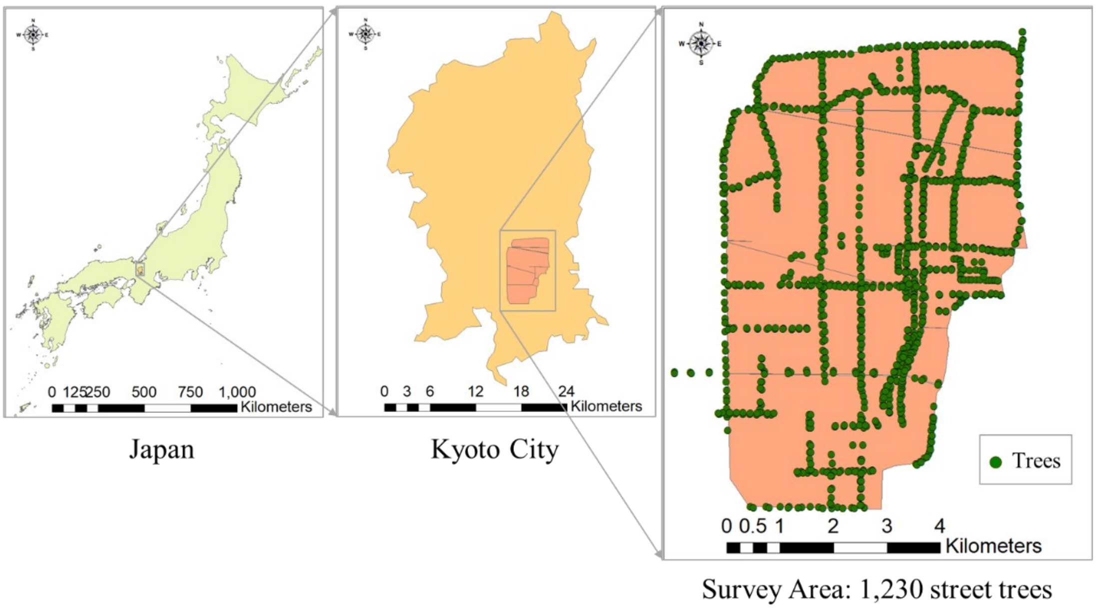


Figure 4. 1 Location of sample street trees in the urban area of Kyoto City.

data stored in the server are globally available, even users in other countries can use i-Tree Eco with their local location, air quality, and precipitation data uploaded to the server via i-Tree Database (ITDB) (www. database.itreetools.org). However, this path only enables users to use their local data; it is impossible for the model itself and parameters to be modified for their use in their own countries.

The ES provided by trees that i-Tree Eco can estimate include (1) carbon storage and sequestration, (2) air pollution removal, (3) human health effects associated with air pollution removal, (4) heating and cooling energy savings in houses, and (5) stormwater runoff avoided. The models for (1), (2), and (5) are readily applicable to countries other than the US using the local data that are made available with ITDB. On the other hand, since the models for (3) and (4) were originally developed based on the methods and data applicable to the US only, the application of these models to countries outside the US is very limited.

This study estimated (1) to (5) based on street tree measurements in Kyoto. The i-Tree Eco's limitations existing outside the US were greatly reduced by modifying the model codes as well as parameters with the cooperation of an i-Tree developer. Table 4.1 presents the input data/parameters for each model with a notation of customization conducted in this study, and the following sections explain each model and customizations conducted for models of (3) and (5).

Carbon storage and sequestration

It was necessary to identify the correspondence between tree species found in Kyoto city and those in i-Tree Eco's species database to calculate carbon storage and sequestration into trees. Other than that, no customization for the codes, parameters, and data was necessary. Based on the property of each tree species, dry biomass for woody parts as well as leaves was calculated using the methods described in Nowak et al., (2008, 2013a). Half of the dry biomass of trees was estimated as the carbon stored in trees. The growth of a tree was estimated for each tree species based on the health condition and planted site characteristics (e.g., crown light exposure) of the tree. The gross amount of carbon sequestered annually into a tree was then calculated from the difference in estimates of carbon storage between the current and next year (Nowak et al., 2008, 2013a).

Air pollution removal

Based on tree structures such as tree cover and evergreen percent in the study area as well as the leaf area index (LAI) estimated with i-Tree Eco, the removal of carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), particulate matter less than 2.5 μm ($PM_{2.5}$), and sulfur dioxide (SO_2) were estimated as described by Hirabayashi et al. (2011; 2015) and Nowak et al. (2013b). Input data for the model (i.e., surface weather, upper air, and air pollutant data) from the local monitoring stations were employed here (Table 4.1). Although the parameters for the model were not optimized, the model itself was optimized to use local measurements of solar and net radiation rather than calculating these based on the extraterrestrial solar constant, coordinate, and other atmospheric properties (e.g., ozone depth and albedo), which is the default model implementation in i-Tree Eco.

Table 4. 1 Model input data and parameters used for i-Tree Eco run for Kyoto City

Model	Input Data/Parameter	Value/ID/Monitor	Data Year	Reference
Carbon Storage/ Sequestration	Social cost of CO_2 [a]	51.2US$/t	2018	IWG, 2016
Air Pollutant Removal	Latitude [b]	35.0117	-	-
	Longitude [b]	135.768	-	-
	Time zone [b]	UTC + 9	-	-
	Leaf-on date [b]	Apr. 4th	1981–2010	JMA, 2018
	Leaf-off date [b]	Nov. 18th	1981–2010	JMA, 2018
	Surface weather [a]	477590: Kyoto	2015	NCEI, 2019
	Upper air [a]	47778: Shionomisaki	2015	ESRL, 2019
	Solar radiation [c]	26104060: Mibu	2015	NIES, 2019
	Net radiation [c]	28204150: Hamakoushien	2015	NIES, 2019
	Precipitation [b]	28214010: Yoriaihiroba	2015	NIES, 2019
	CO concentration [b]	26104510: Jihaioomiya	2010–2015	NIES, 2019
		26107510: Jihaiminami	2010–2015	NIES, 2019
	NO_2 concentration [b]	26101010: Kita	2010–2015	NIES, 2019
		26102510: Jihaikamigyou	2010–2015	NIES, 2019
		26103010: Sakyou	2010–2015	NIES, 2019
		26104010: Kyoutoshiyakusho	2010–2015	NIES, 2019
		26104060: Mibu	2010–2015	NIES, 2019
		26104510: Jihaioomiya	2010–2015	NIES, 2019
		26107510: Jihaiminami	2010–2015	NIES, 2019
	O_3 concentration [b]	26101010: Kita	2010–2015	NIES, 2019
		26103010: Sakyou	2010–2015	NIES, 2019
		26104010: Kyoutoshiyakusho	2010–2015	NIES, 2019
		26104060: Mibu	2010–2015	NIES, 2019
	$PM_{2.5}$ concentration [b]	26102510: Jihaikamigyou	2010–2015	NIES, 2019
		26104010: Kyoutoshiyakusho	2010–2015	NIES, 2019
		26104060: Mibu	2010–2015	NIES, 2019
		26104510: Jihaioomiya	2010–2015	NIES, 2019
		26107510: Jihaiminami	2010–2015	NIES, 2019
	SO_2 concentration [b]	26104060: Mibu	2010–2015	NIES, 2019
Human health effects	Population [b]	451,462 (total)	2015	Kyoto City, 2018
	Medical expense [c]	46% of the US	2018	OECD, 2019a
	Household income [c]	65% of the US	-	OECD, 2019b
	Value of a statistical life [c]	3,909,090.91 US$	1991–2007	Miyazato, 2010
Energy savings	Building [c]			GSI, 2018
	Tree/building cover [c]	52%		GSI, 2018
	Years constructed [c]	-	-	Kyoto pref., 2018
	Number of houses [c]	692,800 (total in Kyoto)	2015	Kyoto pref., 2018
	CO_2 emission Coefficient			
	Electricity [c]	0.509 kg-CO_2/kWh	2015	MoE, 2019
	Natural gas [c]	53.70 kg-CO_2/MBTU	2015	Daigas Group, 2019
	Heating oil [c]	71.53 kg-CO_2/MBTU	2015	MoE, 2019
	LPG [c]	62.25 kg-CO_2/MBTU	2015	Japan LPGA, 2019
	Price			
	Electricity [b]	0.23 US$/kWh	2015	KEPCO, 2018
	Natural gas [b]	33.68 US$/MBTU	2015	Daigas Group, 2019
	Heating oil [b]	24.20 US$/MBTU	2015	Agency NRE, 2019
	LPG [b]	67.11 US$/MBTU	2015	Oil Info. Center, 2019
Avoided runoff	Surface weather [a]	477590: Kyoto	2015	NCEI, 2019
	Precipitation [b]	28214010: Yoriaihiroba	2015	NIES, 2019
	Impervious cover [c]	80.57%	2014–2016	JAXA, 2019
	Stormwater control cost [d]	2.36 US$/$m^3$	2007	Vargas, et al., 2007

[a]: Globally applicable data/parameter.
[b]: Replaceable with local data/parameter via i-Tree Database; also replaced in this study.
[c]: Customized in this study.
[d]: Parameter for the US and employed in this study.

Human health effects associated with air pollution removal

i-Tree Eco estimates avoided adverse health incidences and costs associated with changes in NO_2, O_3, $PM_{2.5}$, and SO_2 concentration due to the removal of pollution by trees (Nowak et al., 2013b, Hirabayashi and Nowak, 2016) with BenMAP (US EPA, 2020) incorporated into i-Tree Eco. BenMAP was developed by the US Environmental Protection Agency by consolidating the human medical records and air quality measurements across the US with the knowledge gained from statistical analyses of those data.

Based on seven concentration change metrics, 13 adverse health endpoints can be analyzed with BenMAP. The concentration changes metrics include the annual mean of daily 1 h maximum (1Max), daily mean for 8–10 a.m. (3Mean), daily mean for 6–9 a.m. (4Mean), daily maximum for 8 h moving average (8Max), daily mean for 9 a.m–4 p.m. (8Mean), daily mean (24Mean), and the quarterly mean of the daily mean (24MeanQ). The 13 adverse health endpoints analyzed include Acute Respiratory Symptoms (ARS), Emergency Room Visits (ERV), and Hospital Admissions, Respiratory (HAR) caused by exposure to NO_2, O_3, $PM_{2.5}$, and SO_2, Asthma Exacerbations (AE) caused by exposure to NO_2, $PM_{2.5}$, and SO_2, mortality (M) caused by exposure to O_3 and $PM_{2.5}$, Acute/Chronic Bronchitis (AB/CB), Acute Myocardial Infarction (AMI), Hospital Admissions, Cardiovascular (HAC), Upper/Lower Respiratory Symptoms (URS/LRS), and Work Loss Days (WLD) caused by exposure to $PM_{2.5}$, and school loss days (SLD) caused by exposure to O_3.

In BenMAP, correlations between changes in concentration metrics of air pollutant, ΔC_i, and changes in adverse health incidences, ΔI_i for the age group population, P_i, and accompanying changes in medical expenses, ΔV_i are defined with 85 health effect functions for each county in the US, where i represents a function number. For example, $i = 58$ defines the relationship between the change in 1Max of NO_2 and the change in HAR incidences and medical expenses in the age group 0–14 years old. In Los Angeles County, California, where the population P_i of the age group 0–14 years old is the largest in the US (about 2 million people), $\Delta C_{58} = 12.3$ μg/m^3, whereas $\Delta I_{58} = 228$ and ΔV_{58} = US \$663 million.

For each county, P_i was derived from the 2010 US Census, ΔC is the change in the metrics in each county between the maximum (baseline year) and minimum (control year) concentrations within the period of 2000–2007.

When integrating BenMAP's 85 health effect functions into i-Tree Eco, the incidence multiplier, IM_i (case/ppb/person or case/μg/m^{3}/person), which is the incidence per unit change in concentration per person for each county, was estimated from Equation (1) below. Similarly, the value multiplier, VM_i (US\$/ppb/person or US\$/μg/m^3/person), which is medical expenses per unit change in concentration per person for each county, was estimated from Equation (2).

$$IM_i = \frac{\Delta I_i}{P_i \cdot \Delta C_i} \tag{1}$$

$$VM_i = \frac{\Delta V_i}{P_i \cdot \Delta C_i} \tag{2}$$

This integration enabled to calculate reduction in adverse health incidences, ΔI and reduction in medical expenses, ΔV based on change in air quality concentration metric, ΔCi that is caused by trees, and population, P_i and these multipliers, IMi, VMi. For example, reduction in HAR associated with NO_2 for ages from 0- to 99-years can be calculated by:

$$\Delta I = IM_{58} \cdot P_{58} \cdot \Delta C_{58} + IM_{59} \cdot P_{59} \cdot \Delta C_{59} + IM_{64} \cdot P_{64} \cdot \Delta C_{64} \qquad (3)$$

where P_{58}, P_{59}, and P_{64} are populations for age groups 0–14, 15–64, and 65–99, respectively. ΔC_{58} and ΔC_{59} are both changes in 1Max of NO_2, and ΔC_{64} represents the change in 24Mean of NO_2. To calculate the reduction in the medical expenses, the corresponding VMi is used in Equation (3).

For Kyoto, the medical records for each age group associated with air quality measurements that could replace the BenMAP analyses were not readily available. Hence, the parameters, IMi and VMi, were modified for Kyoto based on the assumption that the response of humans to air pollution is the same, whether it is in the US or in Japan. In this process, the years for the maximum (baseline year) and minimum (control year) annual mean concentrations from 2010 to 2016 were first identified for each of the four air pollutants in Kyoto. All the US counties were then searched to identify those that had the closest concentration for baseline and control years as well as the change between the two years for each of the seven metrics for each air pollutant. A reference US county for each metric for each air pollutant was assigned to Kyoto through these processes. Adverse health incidence for each endpoint for each age group was adjusted based on the population ratio between Kyoto and the reference counties. Monetary values per incidence were adjusted based on the ratio (46%) of the mean medical expenses between Japan and the US (OECD Data, 2019a). For WLD and SLD, the monetary value per incidence was adjusted based on the ratio (65%) of the mean household income between Japan and the US (OECD Data, 2019b). For the monetary value for M, the median value for a statistical life (VSL) derived from the literature in Japan (Miyazato, 2010) was employed.

Heating and cooling energy savings in houses

Based on McPherson and Simpson (1999) and Nowak et al. (2017), i-Tree Eco estimates changes in heating and cooling demands for houses with two or fewer floors based on shade, windbreak, and transpiration effects by trees with 6 m or taller and located within 18 m from the house and windbreak effects by other buildings.

In i-Tree Eco, for 11 climate regions in the US, the base values of CO_2 emission change because of changes in demands for cooling and heating due to tree shade and windbreak effects are stored in look-up tables for the combination of the three house vintages (pre-1950/1950–80/post-1980), leaf type (deciduous/evergreen), tree height (6–10/10–15/15 m or taller), the distance between a tree and a house (0–6/6–12/12–18 m), and eight directions from a house to a tree. In addition, the base CO_2 emission changes because of changes in the heating and cooling demands affected by the transpiration from trees and the windbreak by buildings are stored in look-up tables for 10%, 30%, and 60% of trees and building covers combined in each climate region.

It was ideal if this kind of base values of CO_2 emission change due to tree effects were readily available in Kyoto, but it was not the case. Thus, based on the assumption that human's demand for cooling and heating is same in the US and Japan, these look-up tables were used in this study by referencing a US climate region that best fits the climate in Kyoto. The approach requires four steps: (1) from 16 cities representing each US climate zone defined in McPherson, (2010), six candidate reference cities (RCs) were selected by comparing heating degree days (HDDs), cooling degree days (CDDs), and annual precipitation with the subject city (SC), Kyoto; (2) the root mean square error (RMSE) of climatic variables between the RCs and SC was calculated using Equation 4, where a, b, and c are positive weighting coefficients that add to 1.0, expressing the relative importance of each variable, (3) one RC with the minimum RMSE was selected as the reference city for Kyoto, and (4) a climate region in which the selected RC falls into is selected from i-Tree Eco's 11 climate regions (McPherson and Simpson, 1999).

$$\text{RMSE} = \sqrt{a(HDD_{SC} - HDD_{RC})^2 + b(CDD_{SC} - CDD_{RC})^2 + c(AP_{SC} - AP_{RC})^2} \quad (4)$$

In the US, the thermal resistance (R-value) for each part (wall, ceiling, window, floor, and foundation) of the default housing for each vintage for each climate region are defined (McPherson and Simpson, 1999), whereas, in Japan, the heat loss coefficient (Q-value) for an entire house is defined as an energy conservation standard (Toyama, 2013). By integrating housing parts with R-value into the entire house, the Q-value for the default house was calculated, which, in turn, was compared to the standard in Japan to identify the match of the house vintages between the US and Japan.

Building data for Kyoto was obtained from the Geospatial Information Authority of Japan (GSI), (GSI, 2018). Residential houses were identified with a footprint of 100 m_2 or less, based on an average footprint of the area (Kyoto Residential Area Ranking, 2019), and the direction and distance between the closest tree to each house were calculated using a geographical information system (GIS). Trees less than 6 m in height were excluded in this study because they are too low to affect the energy use in nearby houses. Houses located farther than 18 m from the nearest street tree were excluded as they were too far from the tree for their energy use to be affected.

Avoided stormwater runoff

i-Tree Eco estimates avoided stormwater runoff based on Hirabayashi (2013), in which storm water runoff for two scenarios, (1) with the current tree cover and (2) with no tree cover in the study area, were calculated. The difference between the two scenarios was considered avoided stormwater runoff because of the existence of the trees. Within the model, hourly precipitation, rainfall intercepted by tree leaves determined based on LAI, evaporation from leaves, rainwater dropped to the ground, infiltration of the pervious cover, and runoff from the impervious cover were calculated based on Wang et al. (2008). One limitation here is that because the soil information is not available in i-Tree Eco, it was assumed that all the rainwater reaching the pervious cover infiltrates into the ground, while the rainwater reaching the impervious cover all runoffs. Average impervious and pervious covers for the study area were determined based on JAXA's ALOS-2 land cover data (JAXA, 2019), and it was assumed that these values were uniform across the study area. The valuation for the avoided runoff was performed with the default value in i-Tree Eco, which is 2.36 US$/$m^3$ for stormwater control facilities in the US.

4.3. Results

4.3.1. Species composition

The nine most widely planted species were *G. biloba* (47.80%), *A. buergerianum* (14.15%), *Z. serrata* (8.13%), *L. tulipifera* (6.18%), *C. florida* (4.80%), *P. × acerifolia* (4.15%), *P. × yedoensis* (3.41%), *P. jamasakura* (2.20%), and *S. babylonica* (1.22%). *G. biloba* was the most dominant species, accounting for approximately half of the total population. The three most abundant tree species, which covered 67.91% of the total leaf area, were *G. biloba* (33.50%), *Z. serrata* (19.59%), and *A. buergerianum* (14.82%), whereas *Z. serrata* (255.67 m^2/tree), *P. × yedoensis* (174.17 m^2/tree), and *P. × acerifolia* (159.36 m^2/tree) provided the most leaf area on a per tree basis (Table 4.2).

4.3.2. Size distribution

The size distribution (in terms of diameter at breast height, DBH) is a key factor in managing a resilient tree population, influencing present and future costs as well as the flow of ecological benefits (McPherson and Rowntree, 1989).

The DBH structure of street trees in Kyoto city was distributed unevenly comparing to the "ideal" size distribution proposed by Richards (1983), with a preponderance of maturing (15–30 cm DBH), mature (30–45 cm DBH) street trees, which account for 43.90% and 33.30%, respectively. The distribution indicated that many of Kyoto city's street trees were planted 20 to 50 years ago, and they provide maximum benefits because of their size and condition. There is a paucity of young, small-diameter classes (0–15 cm DBH), where the proportion is 17.8% lower than the ideal for offset establishing-related mortality. The species most heavily represented in the large, mature classes (>30 cm DBH) included *Z. serrata* (66.70%), *A. buergerianum* (49.50%), *P. × acerifolia* (51.00%), and *S. babylonica* (76.30%). Notably, *P. × yedoensis* (31.00%) was present in old tree classes (>60 cm DBH), offering extensive ecological services in Kyoto city (Figure 4.2).

Table 4. 2 Predominant street tree species and their leaf area

Species	Total Tree Numbers	Avg. Tree Height (m)	Avg. DBH (cm)	Leaf Area(m^2)		
				Avg.	Total	% of Total
Ginkgo biloba	588	8.55	26.10	74.34	43,712.71	33.50
Acer buergerianum	174	8.76	29.21	111.12	19,335.92	14.82
Zelkova serrata	100	11.94	35.47	255.66	25,566.32	19.59
Liriodendron tulipifera	76	8.41	19.08	116.03	8,818.77	6.76
Cornus florida	59	4.90	10.34	54.28	3,203.04	2.45
Platanus ×acerifolia	51	9.74	30.14	159.36	8,127.75	6.23
Prunus × yedoensis	42	7.94	49.26	174.17	7,315.23	5.64
Prunus jamasakura	27	6.30	20.59	110.66	2,988.00	2.29
Salix babylonica	15	8.91	34.08	109.38	1,640.84	1.25
Other species	98				9,750.37	7.47
Total	1,230				130,458.95	100.00

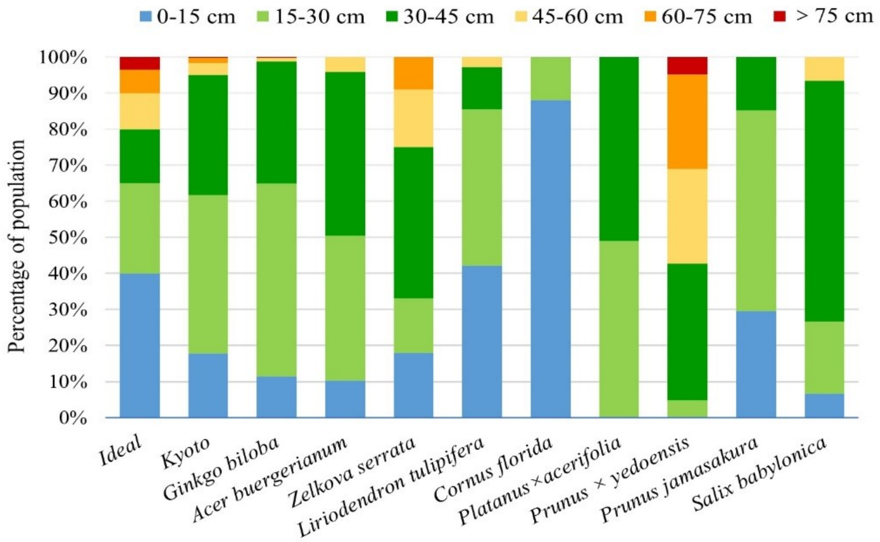


Figure 4. 2 DBH size distribution of predominant street tree species compared to an "ideal" distribution (Richards, 1983). Note: The "Kyoto" classification represents the total of the sampled street trees

4.3.3. Ecosystem services

Carbon Storage and Sequestration

Kyoto City's 1230 sample street trees were estimated to store 244.782 t (US$47,852.61) in their biomass, and the gross sequestration per year was approximately 15.365 t (US$3000.43). *G. biloba* (38.36%), *Z. serrata* (17.42%), and *P. × yedoensis* (17.21%) stored and sequestered the greatest amount of carbon due to their numbers and age. On a per tree basis, the carbon storage and sequestration benefits were US$41.34/tree on average. *P. × yedoensis* produced the greatest net value at approximately US$200.47/tree. Moreover, *Z. serrata* (US$85.23/tree) and *S. babylonica* (US$62.44/tree) also significantly contributed to offset carbon emissions. Conversely, *C. florida* (US$4.22/tree), *L. tulipifera* (US$16.01/tree), and *P. jamasakura* (US$27.54/tree) were well below the average value (Table 4.3).

Table 4. 3 Predominant street tree species and their annual carbon storage and sequestration values in Kyoto City.

Species	Carbon Storage (kg)			Carbon Sequestered (kg/Year)			Total Value ($)
	Avg.	Total	Value ($)	Avg.	Total	Value ($)	
Ginkgo biloba	156.64	92,107.67	17,316.24	13.08	7,693.40	1,446.35	18,762.59
Acer buergerianum	207.80	36,158.83	6,797.86	14.68	2,554.77	480.27	7,278.13
Zelkova serrata	435.42	43,542.36	8,185.96	17.95	1,795.50	337.55	8,523.51
Liriodendron tulipifera	77.82	5,914.48	1,111.92	7.37	560.32	105.34	1,217.26
Cornus florida	18.81	1,110.04	208.68	3.64	214.92	40.40	249.08
Platanus ×acerifolia	200.55	10,228.19	1,922.90	14.88	759.13	142.71	2,065.61
Prunus × yedoensis	1039.25	43,648.77	8,205.94	27.10	1,138.38	214.01	8,419.95
Prunus jamasakura	138.02	3,726.60	700.69	8.49	229.41	43.12	743.81
Salix babylonica	316.87	4,753.12	893.58	15.27	229.15	43.07	936.65
Other species		3,592.93	2,508.84		190.91	147.61	2,656.45
Total		244,782.99	47,852.61		15,365.89	3,000.43	50,853.04

Air pollutant removal & avoided stormwater runoff

Air pollution removal was estimated at approximately 178.26 kg (30.82 kg for NO_2, 121.79 kg for O_3, 10.90 kg for $PM_{2.5}$, and 14.75 kg for SO_2) annually (Table 4.4). Kyoto's sample street trees intercepted approximately 1699.39 m^3 of rainfall annually, and this effect was associated with the benefits of stormwater runoff reduction at US$4011.76 (Table 4.4). On average, each street tree contributed to an intercept of 1.38 m^3 of rainfall annually and provided a value of US$3.26. *Z. serrata* (US$7.10/tree), *P. × yedoensis* (US$4.83/tree), and *P. × acerifolia* (US$4.42/tree) had the greatest effect on stormwater runoff reduction benefits.

Table 4. 4 Annual air quality and stormwater effects from sample street trees in Kyoto City.

Species	Total Tree Number	Annual Air Quality Effects				Annual Stormwater Effects	
		NO_2 Removal (g)	O_3 Removal (g)	$PM_{2.5}$ Removal (g)	SO_2 Removal (g)	Avoided Runoff (m^3/Year)	Total Value ($)
Ginkgo biloba	588	8,963.73	38,190.11	3,604.32	4,557.33	514.30	1,214.10
Acer buergerianum	174	3,965.02	16,893.05	1,594.34	2,015.89	227.50	537.04
Zelkova serrata	100	5,242.63	22,336.31	2,108.06	2,665.45	300.80	710.09
Liriodendron tulipifera	76	1,808.37	7,704.62	727.15	919.41	103.75	244.93
Cornus florida	59	656.81	2,798.37	264.10	333.93	37.68	88.96
Platanus ×acerifolia	51	1,666.67	7,100.90	670.17	847.37	95.62	225.74
Prunus ×yedoensis	42	1,500.01	6,391.03	603.17	762.66	86.06	203.17
Prunus jamasakura	27	612.72	2,610.50	246.37	311.51	35.15	82.99
Salix babylonica	15	336.47	1,433.54	135.29	171.06	19.30	45.57
Other species	98	6,068.47	16,338.24	955.01	2,167.68	279.23	659.17
Total	1230	30,820.90	121,796.67	10,907.98	14,752.29	1699.39	4,011.76

Human health effects

Table 4.5 shows the information about US reference counties surveyed for BenMAP calculations. Based on air quality improvement, the avoided incidence of adverse health effects was estimated to be 3.8 cases and the associated economic value of US$14,515.05 annually or US$11.80/tree (Table 4.6). The greatest amount of removal occurred with the O_3 and NO_2 pollutants, while the greatest value associated with removal was for $PM_{2.5}$ and O_3 (Table 4.6). Most of these monetary values were dominated by the effects of reducing human mortality because BenMAP assigns the greatest value per incidence for human mortality by averaging US$3.9 million per incidence (Nowak et al., 2014).

Table 4. 5 Reference US counties for each metric and air pollutant assigned to Kyoto, Japan.

Pollutant	Metric	Kyoto City		Reference Counties		
		Baseline Value	Control Value	State, County	Baseline Value	Control Value
NO_2	1Max	32.56	26.69	Ohio, Richland	32.47	26.64
	4Mean	20.93	17.19	Ohio, Wood	20.80	17.25
	8Max	24.23	19.75	California, San Francisco	24.15	19.77
O_3	24Mean	17.74	14.29	California, Alameda	17.81	14.46
	1Max	53.95	45.37	Illinois, Cook	53.60	45.24
	8Mean	43.04	35.66	North Dakota, Dunn	43.17	36.05
$PM_{2.5}$	8Max	46.16	38.85	Vermont, Franklin	46.43	39.12
	24Mean	32.11	27.42	West Virginia, Boone	32.06	27.43
	24Mean	18.14	12.88	Ohio, Athens	18.19	13.10
	24MeanQ	18.15	12.88	Ohio, Athens	18.19	13.08
SO_2	1Max	6.22	4.46	Iowa, Grundy	6.22	4.60
	3Mean	4.60	3.27	Oklahoma, Okfuskee	4.59	3.27
	8Max	5.20	3.86	Wisconsin, Kewaunee	5.21	3.88
	24Mean	4.25	3.31	Idaho, Cassia	4.15	3.22

Table 4. 6 Annual reduction in adverse health effect incidences and associated monetary value ($) due to pollutant reduction from sample street trees in Kyoto City.

Pollutant	Adverse Health Effect	Incidence (Case)			Value ($)		
			Subtotal	Total		Subtotal	Total
NO_2	Hospital Admissions, Respiratory	0.004	0.696	3.8	52.99	79.04	14,515.05
	Emergency Room Visits, Respiratory	0.001			0.22		
	Asthma Exacerbation	0.650			25.23		
	Acute Respiratory Symptoms	0.041			0.60		
O_3	Acute Respiratory Symptoms	1.335	1.624		52.72	3,191.59	
	Hospital Admissions, Respiratory	0.003			37.37		
	Mortality	0.001			3,083.29		
	School Loss Days	0.284			18.11		
	Emergency Room Visits, Respiratory	0.001			0.10		
$PM_{2.5}$	Acute Bronchitis	0.001	1.394		0.03	11,234.00	
	Acute Myocardial Infarction	0.001			29.99		
	Acute Respiratory Symptoms	0.834			37.79		
	Asthma Exacerbation	0.390			14.65		
	Chronic Bronchitis	0.001			110.99		
	Emergency Room Visits, Respiratory	0.000			0.06		
	Hospital Admissions, Cardiovascular	0.001			11.02		
	Hospital Admissions, Respiratory	0.001			11.01		
	Lower Respiratory Symptoms	0.010			0.24		
	Mortality	0.003			11,005.19		
	Upper Respiratory Symptoms	0.008			0.18		
	Work Loss Days	0.144			12.85		
SO_2	Acute Respiratory Symptoms	0.007	0.069		0.10	10.42	
	Asthma Exacerbation	0.061			2.23		
	Emergency Room Visits, Respiratory	0.000			0.08		
	Hospital Admissions, Respiratory	0.001			8.01		

Heating and cooling cost reduction in houses

US Reference Climate Region for Kyoto

The best match city for Kyoto was Charleston, SC (RMSE = 1.47). Thus, the "US Southeast climate region" was used to model the environmental conditions in Kyoto using i-Tree Eco.

House Vintage Adjustment

Table 4.7 summarizes the R-value to Q-value conversion using Post–1980 vintage houses in the southeast climate region as an example. The inverse of the R-value is the heat transfer coefficient, U-value. The U-value is then multiplied by the area of interest including walls, ceilings, windows, floors, and foundations to obtain the heat loss value. The sum of the heat loss is divided by the floor area to obtain the Q-value, which is 2.45.

Table 4. 7 R-value and Q-value conversion results (post-1980 vintage for the southeast region).

	R-value (m^2 K/W)	**U-value** (W/m^2K)	**Area** (m^2)	**Heat Loss** (W/K)	**Q-value** (W/m^2K)
Wall	1.94	0.52	653.7	337.4	2.45
Ceiling	4.75	0.21	205.5	43.2	
Window	0.40	2.50	24.5	61.3	
Floor	3.35	0.30	205.5	61.4	
Foundation	0.00	0.00	0.0	0.0	

R-values for pre–1950 and 1950–1980 were also calculated with the above-described procedure. Table 4.8 summarizes the energy conservation standards in the US and Japan. The Q-value for post-1996 construction in Japan was 2.7, which is equivalent to that of the post–1980 in the southeast climate region. Therefore, post-1996 houses in Japan were treated as post–1980 houses in the US. Higher Q-values indicate lower insulation capacity. The highest Q-value of 3.79 for Pre–1950 in the US corresponded with pre–1980 and 1981–1995 constructions in Japan.

Table 4. 8 Japanese house vintages assignment to the US's vintages.

US		**Japan**		Count[a]	Ratio[b]
House Vintage	Q-value (W/m^2 K)	House Vintage	Q-value (W/m^2 K)		
Pre-1950	3.79	Pre–1980	5.2	178,280	40.0%
Pre-1950	3.79	1981–1995	4.2	116,290	26.1%
Post-1980	2.45	Post–1996	2.7	151,390	33.9%

[a]: The number of houses that match the house vintage in this study of Kyoto city.
[b]: The ratio of house that matches the house vintage in this study of Kyoto city.

Energy Saving

Among the 1230 sampled street trees, 614 trees affected the energy consumption of 1 or 2-story houses by shading buildings, providing evaporative cooling, and blocking winter winds. The annual energy-related costs were estimated at US$2054.36 using customized parameters (Table 4.9).

Table 4. 9 Annual energy savings and monetary values provided by street trees in Kyoto City.

Leaf Type	Direction	Mean Distance (m)	Tree Count	Mean DBH (cm)	Mean Leaf Area (m^2)	Mean Height (m)	Electricity ($)	Fuel ($)	Total ($)
Deciduous	N	8.6	81	26.68	92.29	8.53	211.61	100.10	311.71
Deciduous	NE	7.5	56	28.22	93.54	8.63	132.57	58.01	190.58
Deciduous	E	7.8	99	29.02	109.82	9.11	749.00	−168.32	580.67
Deciduous	SE	6.4	67	30.77	120.35	9.17	91.56	−202.98	−111.42
Deciduous	S	7.2	80	26.49	102.44	8.52	25.54	−525.78	−500.23
Deciduous	SW	9.2	55	29.10	112.25	9.01	47.58	−268.79	−221.20
Deciduous	W	7.6	102	27.58	111.99	8.82	1,911.60	−524.61	1,386.98
Deciduous	NW	7.8	64	28.84	110.72	8.85	278.53	64.52	343.05
Evergreen	NE	15.6	1	33.00	101.92	6.50	3.72	3.24	6.97
Evergreen	E	2.0	1	22.00	47.69	6.40	3.78	−1.02	2.76
Evergreen	S	8.6	2	36.25	212.94	7.70	0.01	−4.70	−4.69
Evergreen	SW	9.8	1	23.50	121.23	8.80	1.44	−0.54	0.89
Evergreen	W	12.5	5	29.96	72.08	8.00	63.65	4.63	68.29
Total			614				3,520.59	1,466.24	2,054.36

Note: negative numbers indicate that there was no reduction in carbon emissions and/or value, and instead, carbon emission and values increased by the amount reported as negative

Annual net benefits and costs

Annual benefits

The total annual value of sample street trees was evaluated by summing the four different estimated ES benefits which were calculated at US$71,434.21 annually or US$58.07 per tree on average (Table 4.10). The largest benefits were carbon storage and sequestration, which accounted for 71.19% of the total benefits. In contrast, energy savings contributed the least to ES, at only 2.88% of the total benefits (Table 4.10). On a per tree basis, *P. × yedoensis* (US$225.32/tree), Z. serrata (US$123.21/tree), *S. babylonica* (US$80.10/tree), and *P. × acerifolia* (US$65.88/tree) produced significant benefits, whereas *C. florida* (US$11.78/tree), *L. tulipifera* (US$33.64/tree), *P. jamasakura* (US$43.31/tree), and *G. biloba* (US$43.74/tree) produced the least benefits (Table 4.11).

Expenditures

Based on the information provided by the Green Policy Promotion Office of the Kyoto City Construction Bureau, the municipality of Kyoto spent exceed US$4,500,000 to maintain the population of 50,000 street trees annually including the costs of pruning, cleaning the fallen leaves, and pest and disease control. The average annual street tree expenditure is estimated at US$90 (90 = 4,500,000/50,000) (Kyoto City Construction Bureau, personal communication). Results are reported in U.S. dollars, economic data collected in Japanese Yen were converted to U.S. dollars using an exchange rate of 1U.S. dollar to 110 Yen (Table 4.10).

Table 4. 10 Annual benefits-cost summary of sample street trees.

	Monetary Value ($)	**% of Total Benefits**	**Value /Tree ($)**
Benefits			
Carbon storage & sequestration (C)	50,853.04	71.19	41.34
Stormwater runoff reduction (S)	4,011.76	5.62	3.26
Adverse health mitigation (A)	14,515.05	20.32	11.80
Energy saving (E)	2,054.36	2.88	1.67
Total (C+S+A+E)	71,434.21	100.00	58.07
Tree management cost			90.00

Table 4. 11 Monetary value of predominant street tree species in Kyoto City.

Species	Total Tree Numbers	Avg. Tree Height (m)	Avg. DBH (cm)	Avg. Leaf Area (m^2)	$/Tree
Ginkgo biloba	588	8.55	26.10	74.34	43.74
Acer buergerianum	174	8.76	29.21	111.12	58.73
Zelkova serrata	100	11.94	35.47	255.66	123.21
Liriodendron tulipifera	76	8.41	19.08	116.03	33.64
Cornus florida	59	4.90	10.34	54.28	11.78
Platanus ×acerifolia	51	9.74	30.14	159.36	65.88
Prunus × yedoensis	42	7.94	49.26	174.17	225.32
Prunus jamasakura	27	6.30	20.59	110.66	43.31
Salix babylonica	15	8.91	34.08	109.38	80.10

4.4. Discussion

This study in Kyoto is the first attempt to use the empirical data in quantifying the ES of street trees, and the results could provide the municipality with base-line values for future management.

Our results indicate that large-growing species with more leaf area, such as *P. × yedoensis* (174.17 m^2/tree, US$225.32/tree), *Z. serrata* (255.66 m^2/tree, US$123.21/tree), and *P. × acerifolia* (159.36 m^2/tree, US$65.88/tree) appeared to be the most valuable species in Kyoto city, which reflects the importance of the leaf area is the driving force behind the ability of trees to offer ecological benefits for the community. Many previous studies have pointed out that tree canopy cover and leaf area play a key role in determining the delivery of ES. The greater the tree canopy size, the greater the pollution removal and precipitation intercept, and the greater the value provided (Lin et al., 2019; Nowak et al., 2014; Peper et al., 2007; Rogers et al., 2015). Maintaining the health and longevity of these large trees is critical to achieving high ES levels in Kyoto city.

4.4.1. Benefits-Cost Comparison

Regarding the benefits-cost ratio, it was demonstrated that the value of the annual benefits generated by street trees in Kyoto City did not outweigh tree-related expenditure. This finding could be explained by three factors: first, the most dominant species, *G. biloba* (US$43.74/tree), which accounted for 47.8% of the entire population, also had a low tree canopy cover and therefore provided a low level of benefit. In Kyoto City, the average leaf area of *G. biloba* (74.34 m2/tree) (DBH=26.1 cm, height = 8.55 m) is considerably lower than that of the same species in other cities. Peper et al. (2001) predicted the size of 12 common street trees growing in Modesto, CA, USA, and showed that the leaf area of *G. biloba* was 235.29 m2/tree (DBH = 38.7 cm, height = 11.74 m). The difference may be primarily due to the street tree management practices implemented in Kyoto City. The conflict between street tree expansion and constrained planting space is prominent in Japan, resulting heavy pruning, which suppresses the growth of tree canopy (Fujii, 2019).

Additionally, on a per-tree basis, expenditure for street trees in Kyoto City (US$90) is the highest compared with cities in the US and Europe, such as New York City, US (US$37), Santa Monica, US (US$53), Lisbon, Portugal (US$46) (Peper et al., 2007; McPherson and Simpson, 2002; Soares et al., 2011). Considering the need for frequent pruning, the likelihood of increases in the burden of municipal expenditure is very high in Japan (Fujii, 2019).

Furthermore, the estimation of the benefits presented in this study represents only a fraction of the comprehensive value of Kyoto's street trees. In light of the experience from other case studies conducted with the i-Tree Street model, property value accounted for the most important benefits in all cities (Soares et al., 2011). Trees contribute many "other" intangible benefits that are difficult to translate into economic terms, such as biodiversity, beautification, increased human comfort, and sense of place, which cannot yet be factored into the i-Tree Eco model. Kyoto City is a world-famous tourist destination, and street trees in the city are considered a significant attraction for tourists as well as a benefit for urban residents. In recent years, various levels of government in Kyoto have become increasingly aware of the importance of street trees and have made a renewed investment in the median strip planting project. Additional research is needed in this area to provide reliable information on factors such as property attributes, market responses, and willingness to pay.

4.4.2. Advantages

i-Tree Eco is composed of three elements: model codes, model parameters, and input data. One advantage of i-Tree Eco is that it uses model parameters and input data globally applicable or flexibly substitutable to local site-specific values when running it in the region outside the US (Nowak et al., 2008). Those parameters/data globally applicable are denoted with "a" in Table 4.1, including the social cost of carbon and worldwide weather and upper air data stored in i-Tree server computers. Model parameters/input data that an international user can replace via ITDB are location related data, precipitation, air quality and energy prices (denoted with "b" in Table 4.1).

In addition, with the cooperation of an i-Tree developer, the model codes and parameters (denoted with "c" in Table 4.1) were modified in this study. As a result, it has become possible to estimate the air pollution removal and the avoided stormwater runoff by employing solar and net radiations measured in the vicinity of Kyoto rather than estimated values employed in i-Tree Eco.

Regarding the health effects, the analysis available through ITDB for typical international users is very limited. A regression equation for each of the four air pollutants (CO, NO_2, O_3, and $PM_{2.5}$) relating population density and monetary values avoided due to air quality improvement was constructed based on the county-based i-Tree Eco runs across the continental US (Nowak et al., 2014). What typical international i-Tree Eco users can do is to plug their population density into these regression equations to estimate the monetary values. It is impossible for them to calculate the avoided incidence and monetary values for each of the adverse health endpoints. By contrast, our study enabled to quantify these detailed amounts by referencing counties in the US and adjusting their parameters for Kyoto.

Look-up tables utilized in i-Tree Eco to estimate the tree's effects on heating and cooling energy savings at houses across the US were developed based on lots of data collections, modeling, and analyses. These efforts were made possible thanks to funding and collaborations from national laboratories, federal agencies, non-profit organizations, local governments, and utility companies (McPherson and Simpson, 1999) They also provided the instruction on how to determine a reference US climate region for international applications of the method (McPherson,2010), and we followed it. Additionally, we developed a method to replace the US house vintages with those in Japan based on the energy conservation standards in the two countries. This is beyond what common international users can do using ITDB. The method we used in the study may be the best for now when using the look-up tables contained in i-Tree Eco.

4.4.3. Limitations and future directions

Despite the advantages brought by customizing i-Tree Eco's model codes, parameters, and input data, there still exists several limitations and uncertainties in the assumptions and processes conducted in this study, which in turn affect the validity of the results.

The modeled carbon values are estimates based on tree growth allometric equations from the US, and the carbon estimate error includes the uncertainty of using biomass equations and conversion factors (Nowak et al., 2008). It is well known that the growth characteristics of street trees are greatly affected by different management practices and climate conditions. An estimation uncertainty was present in the international case study using surrogate US species data. Currently, there are limited studies that have compiled growth equations for street trees in Japan (Shoda et al., 2020). Future research is needed to develop growth curves to understand the biomass equations for urban trees in Kyoto city with greater accuracy.

With regards to the health effects assessed, adverse health incidences and associated monetary values reduced because of the air quality improvement were estimated based on BenMAP, assuming that the response of humans to air pollution is the same in Japan and in the US. Although the process taken in this study to adjust the health effects in the reference US counties for Kyoto may be plausible when the established methods like BenMAP lack in Japan, there exists uncertainties in the assumption. For instance, susceptibility to air pollution may be affected by many factors such as genetic background, race, ethnicity, and culture (Hooper and Kaufman, 2018) to name a few, which vary between Japan and the US. One future research direction is to explore epidemiologic data and develop methods in Japan that enable analyses like BenMAP.

In the process of the heating and cooling energy saving calculations, the matching of the climate region and the house vintages between Japan and the US were not perfect, hence, uncertainties exist there. It is desirable to develop a similar means to quantify the trees' effects on household energy savings based on the climate and house characteristics in Japan.

Lin et al. (2020) performed thorough sensitivity analyses on several components of i-Tree Eco (i.e., carbon storage/sequestration, bio-emissions, and dry deposition of air pollution) to identify important input variables for each analysis. It is suggested that increasing the accuracy of these important variables is an effective way to reduce uncertainty in the model output. Unfortunately, energy savings, health effects, and stormwater reductions that we assessed in this study were not included in these analyses. Therefore, it will be a great addition to the i-Tree research and user communities if the sensitivity analyses on these three components are performed in the future.

4.5. Conclusions

This chapter describes the first sample tree inventory data-based street tree ES assessment in Kyoto, Japan, by customizing the model and parameters of the i-Tree Eco model. The results presented in this study should be considered first-order estimations of the ES since they were unable to validate against the ground truth due to a lack of such data. Despite that, treating our results as a reference value, they contribute new knowledge on the structure, function, and value of Kyoto's street trees.

For Kyoto City, the annual benefits produced by street trees were estimated at US58.1$/tree. The trees that were estimated to contribute the most to ecosystem services were *P.* × *yedoensis* (US$225.32/tree), *Z. serrata* (US$123.21/tree), *S. babylonica* (US$80.10/tree), and *P.* × *acerifolia* (US$65.88/tree).

Street tree survival, growth, and management in Kyoto City pose a unique set of problems because the majority of street trees are growing in a stressful urban environment that has been impacted and constrained by construction for many years. To maintain the flow of benefits the city currently enjoys, management recommendations derived from this analysis are as follows:

Continue investing in intensive maintenance of large-stature mature trees to prolong the lifespans of tree species such as *P.* × *yedoensis*, *Z. serrata*, and *P.* × *acerifolia*.

To maximize the trees' potential for reducing energy consumption and ensure long-term net benefits from continuous levels of tree canopy cover, heavy pruning should be discontinued, and planting strips should be advocated in new street tree plans.

It is recommended that diversification be continued to reduce dependence on species such as *G. biloba*, while concentrating on selecting tree species that can tolerate restricted site conditions, avoiding unnecessary pruning and management costs.

4.6. References

Agency for Natural Resources and Energy. Available online: https://www.enecho.meti.go.jp/statistics/petroleum_and_lpgas/pl007/results.html (Accessed on 30 /9/2020).

Daigas Group. 2019. Available online: http://www.osakagas.co.jp/company/efforts/eco/co2/evaluation.html (Accessed on 30/9/2020).

Daily, G.C., 1997. Introduction: What are Ecosystem Services; Island Press: Washington, DC, USA,

Dover, J.W., 2015. Green Infrastructure: Incorporating Plants and Enhancing Biodiversity in Buildings and Urban Environments; Routledge: Abingdon, British & New York, USA, pp. 220–227.

Earth System Research Laboratory. NOAA/ESRL Radiosonde Database, 2019. Available online: https://ruc.noaa.gov/raobs/ (Accessed on 30/9/2020).

Fujii, E., 2019. Street Trees Contribute to the City: Walking on the Marathon Course of the Tokyo Olympics; Iwanami Shoten: Tokyo, Japan, pp. 135–140 (In Japanese).

Geospatial Information Authority of Japan (GSI). 2018. Available online: http://www.gsi.go.jp/kiban (Accessed on 30/9/2020).

Hirabayashi, S., 2013. i-Tree Eco Precipitation Interception Model Descriptions. Available online: https://dev.itreetools.org/documents/61/iTree_Eco_Precipitation_Interception_Model_Descriptions.pdf (Accessed on 25/2/2021).

Hirabayashi, S., Kroll, C.N., Nowak, D.J., 2015. i-Tree Eco Dry Deposition Model Descriptions. Available online: http://www.itreetools.org/eco/resources/iTree_Eco_Dry_Deposition_Model_Descriptions.pdf (Accessed on 23/2/2021).

Hirabayashi, S., Kroll, C. N., Nowak, D. J., 2011. Component-based development and sensitivity analyses of an air pollutant dry deposition model. Environmental Modelling & Software, 26(6), 804-816.

Hirabayashi, S., Nowak, D.J., 2016. Comprehensive national database of tree effects on air quality and human health in the United States. Environmental Pollution. 215, 48–57.

Hirabayashi, S., Tan, X., Shibata, S., 2019. Customization of i-Tree Eco's energy saving and health effect models for Japan. Journal of the Japanese Society of Revegetation Technology. 45, 200–203 (In Japanese).

Hirabayashi, S., Tokue, Y., Ito, A., Ellis, A., Hoehn, R., Imamura, F., Morioka, C., 2016. Estimating ecosystem services and their monetary values provided by street trees in Kawasaki ward of Kawasaki city using i-Tree Eco. Journal of the Japanese Society of Revegetation Technology. 42, 4–49 (In Japanese).

Hooper, L.G., Kaufman, J.D., 2018. Ambient Air Pollution and Clinical Implications for Susceptible Populations. Annals of the American Thoracic Society. 15, S64–S68.

Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 2016. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866. Available online:

https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_ 2016.pdf (Accessed on 30/9/2020).

Japan Aerospace Exploration Agency (JAXA). 2019. Available online: https://www.eorc.jaxa.jp/ALOS/lulc/lulc_jindex_v1803.htm (Accessed on 30/9/2020).

Japan LP Gas Association. Available online: http://www. j-lpgas.gr.jp/nenten/co2.html (accessed on 30/9/2020).

Japan Meteorological Agency (JMA). 2018. Available online: https://www.data.jma.go.jp/obd/stats/etrn/index.php (accessed on 30 September 2020).

Japan Meteorological Agency. Normal Value (Value for Each Year/Month) of Meteorological Data. Available online: https://www.data.jma.go.jp/obd/stats/etrn/view/annually_s.php?prec_no=61&block_no=47759&year=&month=&day=&view= (Accessed on 30/9/2020). (In Japanese)

Jim, C.Y., Chen, W.Y., 2006. Recreation–amenity use and contingent valuation of urban greenspaces in Guangzhou, China. Landscape and Urban Planning. 75, 81–96.

Jim, C.Y., Chen, W.Y., 2009. Ecosystem services and valuation of urban forests in China. Cities. 26, 187–194.

Kansai Electric Power Company (KEPCO). Available online: https://kepco.jp/ryokin/menu /dento_a (Accessed on 30/9/020).

Kumar, P., 2012. The economics of ecosystems and biodiversity: ecological and economic foundations. Routledge.

Kyoto City Official, 2010. The Basic Plan for Green of Kyoto City. Available online: https://www.city.kyoto.lg.jp/kensetu/page/0000077122.html (Accessed on 30/9/2020) (In Japanese).

Kyoto City. Population for Kyoto City. 2018. Available online: https://www2.city.kyoto.lg.jp/sogo/toukei/Population/index.html (Accessed on 30 /9/2020).

Kyoto Prefecture Web Site. Available online: http://www.pref.kyoto.jp/tokei/yearly/tokeisyo/ts2015/tokeisyo2015a0618.xls (Accessed on 30/9/2020).

Kyoto Residential Area Ranking. Available online: https://sumaity.com/town/ranking/kyoto/living/?page=2 (Accessed on 30/9/ 2020).

Li, H., Peng, J., Yanxu, L., Yi'na, H., 2017. Urbanization impact on landscape patterns in Beijing City, China: A spatial heterogeneity perspective. Ecological Indicators, 82, 50–60.

Lin, J., Kroll, C.N., Nowak, D.J., 2020. Ecosystem Service-Based Sensitivity Analyses of i-Tree Eco. Arboriculture and Urban Forestry, 46, 287–306.

Lin, J.; Kroll, C.N.; Nowak, D.J.; Greenfield, E.J., 2019. A review of urban forest modeling: Implications for management and future research. Urban Forestry & Urban Greening, 43, 126366.

Livesley, S.J., Baudinette, B., Glover, D., 2014. Rainfall interception and stem flow by eucalypt street trees–The impacts of canopy density and bark type. Urban Forestry & Urban Greening, 13, 192–197.

McPherson, E.G., Rowntree, R.A., 1989. Using structural measures to compare twenty-two US street tree populations. Landscape Journal, 8, 13–23.

McPherson, E.G., 2010. Selecting reference cities for i-Tree Streets. Arboricultural and Urban Forestry, 36, 230–240.

McPherson, E.G., Simpson, J.R., 2002. A comparison of municipal forest benefits and costs in Modesto and Santa Monica, California, USA. Urban Forestry & Urban Greening, 1, 61–74.

McPherson, E.G., Simpson, J.R., 1999. Carbon Dioxide Reduction Through Urban Forestry; US

Department of Agriculture, Forest Service, Pacific Southwest Research Station: Albany, California, USA

Ministry of Environment (MoE). Available online: https://www.env.go.jp/press/files/jp/107786.pdf (Accessed on 30/9/2020).

Ministry of Environment (MoE). Available online: https:// www.env.go.jp/council/16pol-ear/y164-04/mat04.pdf (Accessed on 30/9/2020).

Ministry of Internal Affairs and Communications. Statistics of Japan. Available online: https://www.e-stat.go.jp/en/regional-statistics/ssdsview/ municipality (Accessed on 30/9/2020).

Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and Human Well-Being: Synthesis; Island Press: Washington, DC, USA.

Miyazato, S., 2010. An estimation of value of a statistical life based on labor market data. The journal of Japan Economic Research, 63, 1–28.

Mullaney, J., Lucke, T., Trueman, S.J., 2015. A review of benefits and challenges in growing street trees in paved urban environments. Landscape and Urban Planning, 134, 157–166.

National Centers for Environmental Information (NCEI), 2019. Climate Data Online. Available online: https://www.ncdc.noaa.gov/cdo-web/ (Accessed on 30/9/2020).

National Institute for Environmental Studies (NIES). Environmental value database. 2019. Available online: http://www.nies.go.jp/igreen/ (Accessed on 30/9/2020).

Nowak, D.J., Appleton, N., Ellis, A., Greenfield, E., 2017. Residential building energy conservation and avoided power plant emissions by urban and community trees in the United States. Urban Forestry & Urban Greening, 21, 158–165.

Nowak, D.J., Crane, D.E., 2002. Carbon storage and sequestration by urban trees in the USA. Environmental Pollution. 116, 381–389.

Nowak, D.J., Crane, D.E., Stevens, J.C., 2006. Air pollution removal by urban trees and shrubs in the United States. Urban Forestry & Urban Greening, 4, 115–123.

Nowak, D.J., Crane, D.E., Stevens, J.C., Hoehn, R.E., Walton, J.T., Bond, J., 2008. A ground-based method of assessing urban forest structure and ecosystem services. Arboriculture & Urban Forestry, 34, 347–358.

Nowak, D.J., Greenfield, E.J., Hoehn, R.E., Lapoint, E., 2013. Carbon storage and sequestration by trees in urban and community areas of the United States. Environmental Pollution, 178, 229–236.

Nowak, D.J., Hirabayashi, S., Bodine, A., Hoehn, R., 2013. Modeled PM2. 5 removal by trees in ten US cities and associated health effects. Environmental Pollution, 178, 395–402.

Nowak, D.J., Hirabayashi, S., Bodine, A., Greenfield, E., 2014. Tree and forest effects on air quality and human health in the United States. Environmental Pollution, 193, 119–129.

OECD Data. "Health Spending". 2019a. Available online: https://data.oecd.org/healthres/health-spending.htm (Accessed on 30/9/2020).

OECD Data. Better Life Index. “Income” 2019b. Available online: http://www.oecdbetterlifeindex.org/topics/income/ (Accessed on 30/9/2020).

Oil Information Center. Available online: http://oil-info.ieej.or.jp/price/price_ippan_lp_maitsuki.html (Accessed on 30/9/2020).

Peper, P.J., McPherson, E.G., Mori, S.M., 2001. Equations for predicting diameter, height, crown width, and leaf area of San Joaquin Valley street trees. Journal of Arboriculture, 27, 306–317.

Peper, P.J., McPherson, E.G., Simpson, J.R., Gardner, S.L., Vargas, K.E., Xiao, Q., Watt, F., 2007. New York City, New York Municipal Forest Resource Analysis; Center for Urban Forest Research, USDA

Forest Service, Pacific Southwest Research Station, Davis, California, US.
Peper, P.J., McPherson, E.G., Simpson, J.R., Vargas, K.E., Xiao, Q., Purcell, L., Forester, I.C., 2008. City of Indianapolis, Indiana, Municipal Forest Resource Analysis; Center for Urban Forest Research. US Department of Agriculture, Pacific Southwest Research Station, Tech. Rep. for Indy Parks and Recreation Department: Indianapolis, IN, USA.
Rahman, M.A., Moser, A., Rötzer, T., Pauleit, S., 2017. Microclimatic differences and their influence on transpirational cooling of Tilia cordata in two contrasting street canyons in Munich, Germany. Agricultural and Forest Meteorology, 232, 443–456.
Rahman, M.A., Hartmann, C., Moser-Reischl, A., von Strachwitz, M.F., Paeth, H., Pretzsch, H., Rötzer, T., 2020a. Tree cooling effects and human thermal comfort under contrasting species and sites. Agricultural and Forest Meteorology, 287, 107947.
Rahman, M.A., Moser, A., Anderson, M., Zhang, C., Rötzer, T., Pauleit, S., 2019. Comparing the infiltration potentials of soils beneath the canopies of two contrasting urban tree species. Urban Forestry & Urban Greening, 38, 22–32.
Rahman, M.A., Stratopoulos, L.M., Moser-Reischl, A., Zölch, T., Häberle, K.H., Rötzer, T., Pauleit, S., 2020b. Traits of trees for cooling urban heat islands: A meta-analysis. Building and Environment, 170, 106606.
Raum, S., Hand, K., Hall, C., Edwards, D., O'Brien, L., Doick, K., 2019. Achieving impact from ecosystem assessment and valuation of urban greenspace: The case of i-Tree Eco in Great Britain. Landscape and Urban Planning, 190, 103590.
Richards, N.A., 1983. Diversity and stability in a street tree population. Urban Ecology, 7, 159–171.
Rogers, K., Sacre, K., Goodenough, J., Doick, K., 2015. Valuing London's Urban Forest: Results of the London i-Tree eco Project; Treeconomics: London, UK.
Roy, S., Byrne, J., Pickering, C., 2012. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. Urban Forestry & Urban Greening, 11, 351–363.
Rötzer, T., Moser-Reischl, A., Rahman, M.A., Grote, R., Pauleit, S., Pretzsch, H., 2020. Modelling Urban Tree Growth and Ecosystem Services: Review and Perspectives. In Progress in Botany; Springer: Cham, Switzerland, pp. 1–60.
Shoda, T., Imanishi, J., Shibata, S., 2020. Growth characteristics and growth equations of the diameter at breast height using tree ring measurements of street trees in Kyoto City, Japan. Urban Forestry & Urban Greening, 49, 126627.
Soares, A.L., Rego, F.C., McPherson, E., Simpson, J., Peper, P., Xiao, Q., 2011. Benefits and costs of street trees in Lisbon, Portugal. Urban Forestry & Urban Greening, 10, 69–78.
Tooyama, J. Changes in energy conservation standards and future legislation. Nichias Technol. Time Signal 2013, 360, 6–9. Available online: https://www.nichias.co.jp/research/technique/pdf/360/01.pdf (Accessed on 25/2/2021).
United States Environmental Protection Agency (US EPA). Environmental Benefits Mapping and Analysis Program—Community Edition (BenMAP-CE). 2020. Available online: https://www.epa.gov/benmap (Accessed on 23/2/2021).
US Forest Service, 2020. i-Tree Eco User’s Manual v6.0. Available online: https://www.itreetools.org/documents/275/EcoV6_UsersManual.2020.07.15.pdf (Accessed on 23/2/2021).
Vargas, K.E., McPherson, E.G., Simpson, J.R., Peper, P.J., Gardner, S.L., Xiao, Q., 2007. Temperate

interior west community tree guide: Benefits, costs, and strategic planning. Gen. Tech. Rep. PSW-GTR-206, 108; U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.

Wang, J., Endreny, T. A., Nowak, D. J., 2008. Mechanistic simulation of tree effects in an urban water balance model 1. JAWRA Journal of the American Water Resources Association, 44(1), 75-85.

5. General discussion & conclusion

5.1. Summarization of this study

With the increasing cognization of various economic, social, and environmental benefits of trees, the push for research for the sustainability of urban trees has gained considerable momentum in recent years (Leff, 2016). Our study presents a cogent approach to evaluating the condition and ecosystem services of street trees in Kyoto City, Japan. Chapter two aims to examine the impact of above-ground constrained growing conditions on the health condition of street trees in Kyoto City based on the tree inventories of 1230 samples. Several tree- and site-related variables were collected to identify their impact on tree health. We found that pruning intensity and tree pit size most commonly significantly affected street tree conditions in almost seven species. Trees that were in excellent and good condition accounted for 19.9% and 32.0% of the sample population implied the potential for healthy growth of street trees in the restricted planting spaces of Kyoto City, which suggests appropriate management and planting practices. Chapter three focused on the significantly neglected below-ground part of urban trees aims to track the soil properties factors that predict tree performance in Kyoto City, through empirical data and laboratory soil analysis based on 30 sample street trees of *Ginkgo biloba*. The survey provided evidence that relatively homogeneous streetscape soils in Kyoto City and well-suited for tree growing. The results also identified that soil hardness (50-60 layers) depth might be most strongly influence the tree attributes (*Ginkgo biloba* Linn.). Chapter four based on the inventory data of 1230 street trees, through applying and customizing i-Tree Eco model and parameters aim to understand street tree structure, function, and capture a static snapshot of ecosystem services provided by street trees (e.g., tree size class distribution, species composition, tree species value) in Kyoto City.

By providing this research, the author hopes to elevate the status of street trees as the critical green asset in the urban area for the provision of ecosystem services, as well as contribute to addressing the significant gap in urban tree research in Asia. Furthermore, through this research, the author hopes that the public will be able to improve their scientific and practical understanding of the street trees and take part in the action of maintaining and managing the street trees. There are two main achievements for our studies as follows:

1) Establishing street tree inventory data for the urban area of Kyoto, Japan to reflect and understand the current status, species composition, age distribution, and major factors that affect street trees from above- and below-ground. In general, excessive pruning, limited tree pit size, and soil hardness have been identified to impact the performance of Kyoto City's street trees. At the same time, appropriate tree care management practices implemented by municipal authorities and communities are playing a key role in ensuring the long-term good performance of the street trees.
2) This study presents the first sample street tree inventory data-based ecosystem service assessment in Kyoto, Japan, by customizing the model and parameters of the i-Tree Eco model. Our results as a reference value, not only contribute new knowledge on the wide-ranging benefits, and value of Kyoto's street trees, but also comprehensively demonstrate the street trees as the integral element of the city's green infrastructure to sustain human health and well-being from a budgeting perspective for decision-makers.

5.2. Proposals for management and plan of street trees in Kyoto City

5.2.1. Street tree species selection

The diversity in street tree species is a key to maintaining sustainable urban greening so that their failures would have little effect on the stability of the total street tree population. Increasing the number of species planted in the urban area can contribute to decreasing the risk of failure caused by pests and diseases in the future. In Kyoto City, the most widely planted species was *G. biloba* (47.80%) which accounts for approximately half of the total population. It is recommended that diversification should be continued to reduce overplanting of one species *G. biloba*, while concentrating on selecting other underused tree species that can tolerate restricted site conditions, avoiding unnecessary pruning and management costs.

To incorporate street trees into the streetscape to get the optimum effect, selecting the suitable tree species for the given location is another key aspect in street tree projects. Street tree selection of large and fast-growing species such as *Platanus* spp. trees in Kyoto City should be considered to replace by other species. As suggested by urban forestry experts, the concept of "right tree right place" should be emphasized on street tree selection in Kyoto City (Gangloff, 1999; Flowers and Gerhold, 2000).

Moreover, in the urban area, growing conditions and microclimate can vary from location to location, which were the important factors in determining the final choice of street trees. According to local tree experts and landscape practitioners, the knowledge and information related to the characteristics and tolerance of tree species should be collected and compiled into a central database to facilitate the utilization of such data in the process of tree selection for new street trees planning.

5.2.2. Street tree management and maintenance

Pruning and tree canopy maximization

To maximize the street trees' potential for reducing energy consumption and ensure continuous and long-term ecological benefits/ecosystem services, tree management should be taken to leave a maximum amount of tree canopy by reducing or even avoiding the implementation of heavy pruning.

For example, The Tokyo Metropolitan Government has been started the plan to grow the existing street trees' canopies to enlarge their shade for improving the heat environment of the mid-summer marathon course for the 2020 Tokyo Olympic Games since 2019 (Tokyo Metropolitan Government Construction Bureau, 2019). The canopy expansion strategy formulated varied by different roads, and each road has two expansion directions including the crossing direction and direction along the road. According to the limitation of road space with the different number of lanes, the current tree height will be used to compare with the target tree height index to determine whether it is necessary to increase the height of the trees. Also, the characteristics of tree height and crown growth ratio of different tree species are used to determine whether there is space for tree crown expansion. (Tokyo Metropolitan Government Construction Bureau, 2019). Most importantly, based on the characteristics of different tree species (growth rate, root system, wind resistance, etc.) and different locations, the target tree shape, pruning practice details at the different tree-growth stages are formulated and demonstrated in an easy-to-understand way with figures and photographs in the "Maintenance management plan" (Tokyo Metropolitan Government Construction Bureau, 2019). Under the advice and suggestion of street tree pruning specialists, optimize the pruning method to set the target tree shape that maximizes the tree canopy size within the possible range (Tokyo Metropolitan Government Construction Bureau, 2019).

In addition, it is necessary to reconsider the tree height control pruning method implemented in Japan. Fujii (2019) pointed out that the restrained pruning on the control of street trees height will lead to many branches blowing out from the lower part of the trunk. The example of *G. ginkgo* street tree in Sendai City, Japan showed, after pruning the upper branches and leaves of the vigorous tree canopy, the branches and leaves of the tree crown start to grow chaotically after four or five years. If the pruning of the branches and leaves is not implemented, the tree crown and trunk will grow naturally and remain interval between the branches without the appearance of messy growth (Fujii, 2019).

Tree-friendly planting design

To maximize long-term street tree plant survival, tree-friendly planting design strategies should be handled properly. Many of the urban environmental stresses, including pedestrian and vehicular traffic, soil compaction, and drought can be ameliorated by careful design and after-planting stewardship (Dover, 2015). Although several species are vulnerable to being problematic, most species will produce large surface roots due to the soil conditions being unfavorable (Randrup et al., 2001). Given the circumstances, the tree pit should be as large as possible to allow for ample growing space for tree roots and crowns. The optimal tree pit design would be the continuous tree strip with flexible spacing for roots. Tree pit surface area should be encouraged to plant with grass, shrubs, or flowerbeds. In an extremely narrow roads space that only the single tree pit can be used, it must be paved with a tree grate or guard to prevent trampling and unconscious damage from the pedestrians.

Continued tree aftercare

The species offering extensive ecological services in Kyoto City mostly represented in the large, mature classes included *P. ×yedoensis, Z. serrata, A. buergerianum, P. ×acerifolia,* and *S. babylonica*, because of their size and condition. The intensive maintenance of street trees should be prioritized in these large-stature mature trees to prolong the lifespans. In addition, continue investing in planting young trees planting, the total benefits produced by street trees are vulnerable to fluctuations caused by the death of old trees. Therefore, the municipality of Kyoto needs to consider building a sustainable structure of street trees by new tree plantings to ensure a sustainable street tree structure.

5.3.Future studies

Our research as the first attempt using the empirical data reflecting the street tree performance in Kyoto city, still existing huge research gaps. Our tree inventory data were based on temporary observation and surveys. The static "snapshot" inventory can be used to understand the structure, function, and ecosystem services at a given point in time. There is a need for recognizing the value of long-term repeating investigations data, and only the monitoring data can describe change over time (van Doorn et al., 2019). In the future, the enrichment of real-world data will produce more comprehensive research. In addition, the ecosystem services results based on the i-Tree Eco's model there still exists several limitations and uncertainties in the assumptions and processes conducted in this study. Furthermore, the estimation of the benefits presented in this study represents only a fraction of the comprehensive value of Kyoto's Street trees. Many more intangible tree benefits need to be estimate in the future. Moreover, there is need for more systematic and comprehensive studies for soil part research in Kyoto City. For example, A combination of controlled experiments and in situ testing should be used in the future.

5.4. Reference

Dover, J. W., 2015. Green infrastructure: incorporating plants and enhancing biodiversity in buildings and urban environments. Routledge.

Flowers, D. E., Gerhold, H. D., 2000. Replacement of trees under utility wires impacts attitudes and community tree programs. Journal of Arboriculture, 26(6), 309-318

Fujii, E. Street Trees Contribute to the City: Walking on the Marathon Course of the Tokyo Olympics; Iwanami Shoten: Tokyo, Japan, 2019; pp. 135–140 (In Japanese).

Gangloff, D.,1999. Ten Years and Counting-When it comes to tree planting, stone soup and strange bedfellows make for good partnerships. American Forests, 104, 5-5

Leff, M., 2016. The sustainable urban forest: A step-by-step approach. Davey Institute/USDA Forest Service.

Negoro, C., 2019. For the Tokyo 2020 Games - Measures Against Summer Heat by Enlarging the Canopy of Street Trees-. Construction management technology. Available onlinehttp://kenmane.kensetsu-plaza.com/bookpdf/251/sgb_02.pdf. (Accessed on 31/12/2021) (In Japanese).

Randrup, T. B., McPherson, E. G., Costello, L. R. 2001. A review of tree root conflicts with sidewalks, curbs, and roads. Urban Ecosystems, 5(3), 209-225.

van Doorn, N. S., Roman, L. A., McPherson, E. G., Scharenbroch, B. C., Henning, J. G., Östberg, J. P., Vogt, J. M. 2020. Urban tree monitoring: a resource guide. Gen. Tech. Rep. PSW-GTR-266. Albany, CA: US Department of Agriculture, Forest Service, Pacific Southwest Research Station. 132p., 266.

APPENDIXES

Appendix 1. The street tree species collected by field survey in Kyoto City

Species	Numbers
Ginkgo biloba イチョウ*	588
Acer buergerianum トウカエデ*	175
Zelkova serrata ケヤキ	100
Prunus spp. サクラ属 [a]	88
Liriodendron tulipifera ユリノキ*	77
Cornus florida ハナミズキ*	60
Platanus×acerifolia モミジバスズカケノキ*	52
Salix babylonica シダレヤナギ*	15
Liquidambar styraciflua モミジバフウ*	11
Acer palmatum イロハモミジ	10
Cinnamomum camphora クスノキ	9
Pinus thunbergii クロマツ	8
Lagerstroemia indica サルスベリ*	7
Magnolia kobus コブシ	6
Pinus densiflora アカマツ	5
Cercidiphyllum Japonicum カツラ	5
Ulmus parvifolia アキニレ	4
Triadica sebifera ナンキンハゼ*	3
Celtis sinensis エノキ	3
Liquidambar formosana タイワンフウ*	2
Magnolia denudata ハクモクレン*	2
Firmiana simplex アオギリ	1
Acer pictum Thunb. イタヤカエデ	1
Carpinus laxiflora アカシデ	1

Note: The original field survey sample data included 1233 street trees. Because the data required for analysis in Chapter 2 and Chapter 4 is different, the tree samples used in each Chapter were different due to one or two individual samples with incomplete data collection being excluded from the analysis.

[a] *Prunus* spp. including *Prunus ×yedoensis* Matsum., *Prunus jamasakura* Siebold, *Prunus spachiana* (Lavall,e ex H.Otto) Kitam.

* Denote invasive species.

Appendix 2. Field survey sheet used for street trees inventory data collection in Kyoto city, Japan

Date		**Investigators**		**Weather**	
Species		**Location**			
GPS No.		**Photo No.**			
Growing Environment Condition	Land use	1. Residential 2. Commercial 3. Industrial 4. Others (open space etc.……)			
	Crown Light Exposure	1. One sides 2. Two sides 3. Three sides 4. Four sides 5. Five sides			
	Interaction with surrounding trees	1. None 2. Slightly affected 3. Affected 4. Quite affected 5. Significantly affected			
	Obstruction nearby				
Dimension	Height (m)		D.B.H(cm)		
	Crown height (m)		Diameter at Root Crown (cm)		
	Crown Size (m)	N : S : E : W :			
Ground cover	1. Bare 2. Grass (species record) 3. Shrubs (species record) 4. Pavements (a. gravel/crushed stone b. asphalt/concrete c. others ( )				
	Root lifting (present not) Lift sidewalks or cause cracks (present not)				
Tree pit	1.Simple tree pit (size) 2.Tree planting belts (size)		**Grille**	1.Present (materials) 2. Not	
Management	Pruning	1.Not 2.Present (heavy/medium/weak)	**Tree props**	1.Not 2.Present (materials)	
Comment & Photos					

Appendix 3. Tree decline rating assessment sheet used in Kyoto city, Japan

Parameter		Evaluation criteria 0	1	2	3	4
General Evaluation	Tree vigor	good growth	good condition with slightly decline	obvious decline	significantly decline	near-death
Production (photo-synthetic capacity)	Branch and foliage density	sufficient amount	slightly inferior to 0	slightly sparse	few leaves generated and extremely sparse	no live leave
	Leaf color	dark green throughout the crown	slight light green	slight yellow, reddish-brown	pervasive light green	pervasive yellow, reddish-brown
	Damage of lower crown	none	few not noticeable	lots of conspicuous defects	pervasive twig dieback throughout the crown	no live crown
Hydraulic conductivity/ Nutrient accumulation	Damage/ decay of trunk bark/ sapwood	no noticeable damage/ decay	some damage or decay	conspicuous damage/decay	significant damage/decay	impossible for transmission or accumulation nutrients
Water stress	Leaf (bud) size	plump leaves (buds)	some small leaves (buds)	slight small overall	remarkably small overall	sparse and small leaves (buds)
	Damage of upper crown	none	few not noticeable	lots of conspicuous defects	pervasive twig dieback overall	no live crown
	Base condition	good soil condition for root growth	slightly problematic for root growth	problems with soil condition for root growth	significant problem with soil condition for root growth	root growth significantly inhibited
Growth	Bark metabolism	fresh natural bark color	mostly fresh, with some stale parts	conspicuous stale parts of the bark	dark stale color rather than fresh overall	bark significantly necrotic overall
	Branch extension amount	normal	somewhat less not noticeable	branches are short and thin	branches are extremely short and small	only sprout branches from below grow
Reproduction	Trunk body sprout and basal shoot	sufficient branches and leaves, no trunk body sprout and basal shoot	sufficient branches and leaves exist trunk body sprout and basal shoot	less branches and leaves exist trunk body sprout and basal shoot	less branches and leaves exist many trunks body sprout and basal shoot	sparse branches and leaves exist few trunks body sprout and basal shoot

Appendix 4. Summary of the model for *Ginkgo biloba*

Summary of model				Anova of model	
Model	R Square	Adjusted R square	Standard error of the estimate	*F* ratio	Sig.
1	0.008	0.004	3.8609	2.286	0.103
2	0.097	0.088	3.6951	10.427	0.000
3	0.135	0.120	3.6305	8.966	0.000
4	0.142	0.124	3.6216	7.910	0.000
5	0.148	0.126	3.6176	6.627	0.000
6	0.234	0.211	3.4376	10.204	0.000
7	0.280	0.255	3.3399	11.026	0.000
8	0.285	0.258	3.3320	10.727	0.000
9	0.376	0.352	3.1146	15.475	0.000
10	0.385	0.360	3.0962	15.314	0.000
11	0.397	0.372	3.0673	15.438	0.000
12*	0.404	0.377	3.0537	15.194	0.000

* Denote the selected model

Appendix 5. Summary of the model for *Acer buergerianum*

Summary of model				Anova of model	
Model	R Square	Adjusted R square	Standard error of the estimate	*F* ratio	Sig.
1	0.006	-0.006	3.6023	0.513	0.599
2	0.032	0.010	3.5748	1.425	0.228
3	0.087	0.049	3.5040	2.268	0.031
4	0.101	0.052	3.4973	2.064	0.036
5	0.114	0.043	3.5151	1.594	0.092
6	0.335	0.272	3.0654	5.330	0.000
7	0.362	0.288	3.0308	4.913	0.000
8	0.364	0.286	3.0353	4.669	0.000
9	0.476	0.407	2.7652	6.982	0.000
10	0.512	0.445	2.6764	7.641	0.000
11*	0.539	0.462	2.6351	6.974	0.000

* Denote the selected model

Appendix 6. Summary of the model for *Zelkova serrata*

Summary of model				Anova of model	
Model	R Square	Adjusted R square	Standard error of the estimate	*F* ratio	Sig.
1	0.234	0.218	3.4673	14.817	0.000
2	0.429	0.399	3.0410	14.126	0.000
3	0.534	0.493	2.9948	13.010	0.000
4	0.534	0.481	2.8238	10.192	0.000
5	0.542	0.484	2.8159	9.455	0.000
6	0.619	0.562	2.5958	10.764	0.000
7	0.631	0.560	2.6020	8.866	0.000
8	0.631	0.554	2.6178	8.244	0.000
9*	0.649	0.571	2.5672	8.333	0.000

* Denote the selected model

Appendix 7. Summary of the model for *Prunus.spp*

Summary of model				Anova of model	
Model	R Square	Adjusted R square	Standard error of the estimate	*F* ratio	Sig.
1	0.049	0.027	5.5147	2.195	0.118
2	0.353	0.305	4.6603	7.362	0.000
3	0.354	0.280	4.7442	4.754	0.000
4	0.356	0.263	4.7999	3.818	0.000
5	0.364	0.252	4.8354	3.252	0.000
6	0.513	0.412	4.2867	5.063	0.000
7	0.521	0.412	4.2847	4.817	0.000
8	0.597	0.500	3.9544	6.109	0.000
9	0.653	0.562	3.6997	7.200	0.000
10*	0.656	0.560	3.6096	6.818	0.000

* Denote the selected model

Appendix 8. Summary of the model for *Liriodendron tulipifera*

Summary of model				Anova of model	
Model	R Square	Adjusted R square	Standard error of the estimate	*F* ratio	Sig.
1	0.079	0.054	4.6971	3.182	0.047
2	0.104	0.054	4.6985	2.079	0.092
3	0.163	0.078	4.6386	1.915	0.080
4	0.263	0.164	4.4162	2.657	0.011
5	0.266	0.142	4.4740	2.144	0.029
6	0.588	0.503	3.4056	6.913	0.000
7	0.602	0.496	3.4307	5.666	0.000
8	0.611	0.499	3.4195	6.053	0.000
9	0.653	0.545	3.2589	6.053	0.000
10*	0.695	0.593	3.0810	6.831	0.000

* Denote the selected model

Appendix 9. Summary of the model for *Cornus florida*

Summary of model				Anova of model	
Model	R Square	Adjusted R square	Standard error of the estimate	*F* ratio	Sig.
1	0.330	0.307	4.3225	14.063	0.000
2	0.360	0.314	4.3006	7.749	0.000
3	0.517	0.451	3.8456	7.936	0.000
4	0.532	0.447	3.8603	6.303	0.000
5	0.678	0.612	3.2337	10.311	0.000
6	0.683	0.602	3.2763	8.431	0.000
7	0.709	0.619	3.2051	7.845	0.000
8	0.730	0.638	3.1238	7.933	0.000
9*	0.784	0.704	2.8248	9.770	0.000

* Denote the selected model

Appendix 10. Summary of the model for *Platanus* × *acerifolia*

Summary of model				Anova of model	
Model	R Square	Adjusted R square	Standard error of the estimate	*F* ratio	Sig.
1	0.108	0.071	7.2501	2.954	0.061
2	0.116	0.041	7.3675	1.543	0.205
3	0.152	0.017	7.4591	1.125	0.365
4	0.269	0.090	7.1752	1.506	0.172
5	0.752	0.675	4.2808	9.836	0.000
6	0.789	0.709	4.0562	9.887	0.000
7	0.790	0.702	4.1080	9.002	0.000
8	0.797	0.704	4.0916	8.587	0.000
9	0.848	0.772	3.5953	11.134	0.000
10*	0.875	0.807	3.3087	12.813	0.000

* Denote the selected model

Appendix 11. Three pruning intensity classifications in Japan (*Gingko biloba* as an example)

Natural Tree Shape

Corrective natural tree shape

- Similarly proportionally reduce tree shape
- **Weak pruning level**

Corrective artificial tree shape

- Artificially intentional changed tree shape
- **Medium pruning level**

Trim artificial tree shape

- New artificial shape
- **Strong pruning level**

Source: Authors, July 2018

Source: Authors, July 2018

Source: Authors, July 2018

Appendix 12. Two-stage pruning method in Kyoto, Japan (Matsumoto et al., 2019)

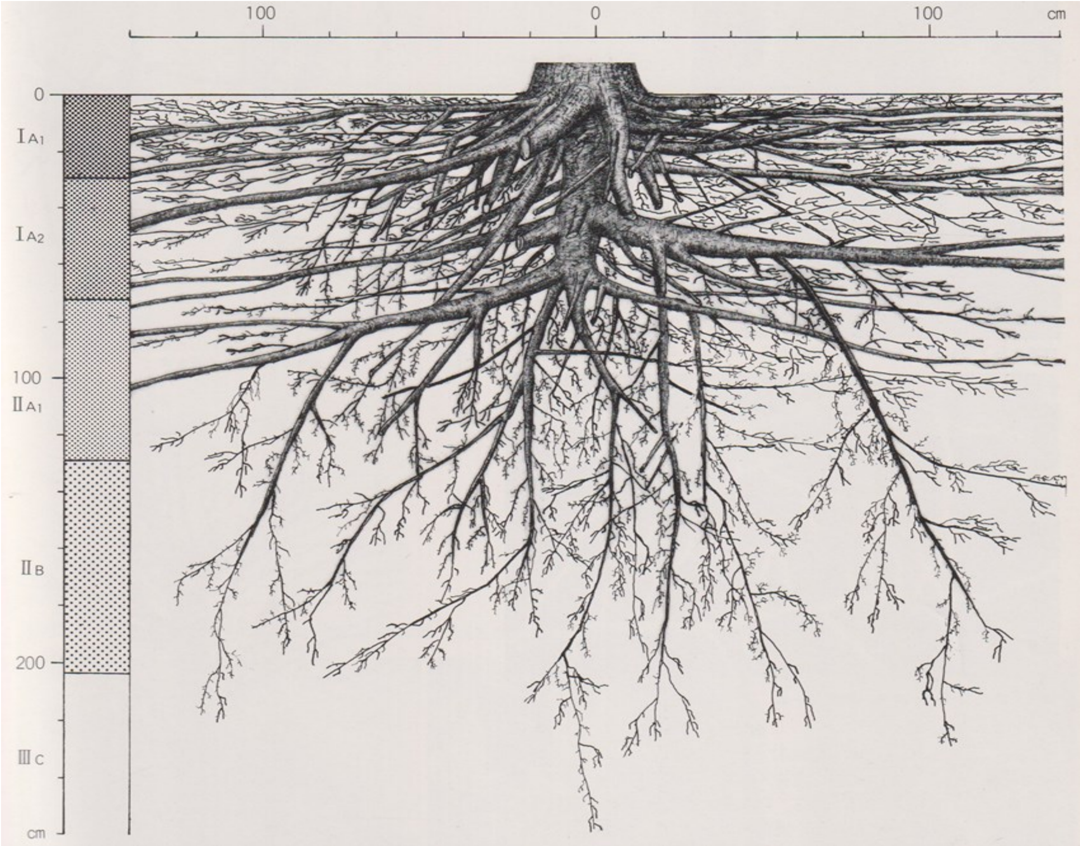
The “two-stage pruning” method was adopted by the Green Policy Promotion Office of Kyoto Construction Bureau as a compromise between creating a landscape of autumn leaves for tourists and citizens, lightening the load of cleaning fallen leaves. Specifically, the first pruning is conducted before the leaves turning color (around October) to trim half of the tree crown, and the second pruning is conducted in the coming year after the autumn leaves (around January to February). Two-stage pruning was conducted every two years. (Kyoto City Official, 2020).

Traditional pruning method (*Gingko biloba* as an example)
 **Before Pruning** **After Pruning**
• Pruning the entire branches and leaves before the leaves turning color • No landscape of autumn leaves and almost no fallen leaves occur
Two-stage pruning method (*Gingko biloba* as an example)
 **Before Pruning** **Autumn Pruning** **Autumn leaves** **Winter Pruning**
• Trimming the half of crown branches and leaves before the leaves turning color • Pruning the tree shape after autumn leaves (winter) • Preserve the landscape of autumn leaves, and the remaining half produce fallen leaves

Matsumoto, A., Fukui, W., Hikishima, D., 2019. Landscape evaluation and economic value evaluation against landscape creation by two-stage pruning of street trees. Journal of the Japanese Institute of Landscape Architecture 12(0), 76-82 (In Japanese).

Kyoto City Office, 2020. What Is the “two-stage pruning” method. (In Japanese). https://www.city.kyoto.lg.jp/kensetu/page/0000109981.html. (Accessed on 13/3/2021)

Appendix 13. Tree root system morphology of Ginkgo biloba Linn. (DBH: 30cm, Total height: 14m, tree age: 40 years, Maximum depth of root of 2.5m) (Karizumi, 1979)



イチョウ科	**イチョウ属**	***Ginkgo***	
土壌	**砂質壌土**	Soil type	Sandy loam
pH	**耐アルカリ性、耐酸性**	pH	Acid-tolerant and Alkali-tolerant
根系の形態	**中・大径の斜出根・垂下根型**	Root system	medium to large diameter tap and oblique roots system
垂直分布	**深根型**	Vertical distribution	Deep tap root with sinker roots growth
水平分布	**中間型**	Horizontal distribution	Medium spreading growth
細根の多さ	**密生型**	Fine roots distribution	Dense and thick fine root growth
細根の太さ	**肥厚型**		

Karizumi, N., 1979. The Illustrations of Tree Roots. Seibundo Shinkosha Publ. Co., Tokyo (In Japanese).