The Variation of Air Purification Benefit Provided by Street Tree Assemblages in Shenyang, China

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Abstract

Street tree assemblages are a widespread natural component in cities and provide a range of ecosystem services. The spatial distribution of street tree assemblages within cities, however, is not uniform. We assessed the air purification benefits provided by street trees in Shenyang, China, to examine how urban form, urban geography and drivers of vegetation management affect this ecosystem service. The i-Tree Street Model was utilized to evaluate air purification benefits provided by street trees. We analyzed the results using two indices, with values expressed in US dollars (USD, $): the per kilometer benefit (PKB) and average tree benefit (ATB). Neither index displayed a consistent trend across the human population density gradient or along the urban-suburban continuum. The district with the highest PKB and ATB is neither the oldest nor the newest one to develop, but rather the one that began to develop around 2002. We conclude that public policy is a main driver of vegetation management, especially for street trees, because street tree abundance is closely related to road construction, which, in turn, is closely tied to economic development in a region. We also discovered no significant difference in the benefit of street tree assemblages along the urban-suburban continuum. That's probably because all areas within the different beltways contain mature street trees, the time-lag effect for growth is inconsequential. We recommend that the dynamic variations of street tree assemblages over a certain time span be taken into consideration when examining the effects of urban sprawl on ecosystem services provided by street tree assemblages.

1 Introduction

Urban ecosystems differ from other natural ecosystems such as rivers, forests, and wetlands. Urban ecosystems consist of both natural and socio-economic components, and are dominated by a single species, i.e. humans. Therefore, urban ecosystems are often considered by ecologists to be damaged or impaired. Nonetheless, some environmental scientists have suggested that the ecosystem services in urban areas can be restored by re-establishment or introduction of appropriate natural components (Wu 2014). A study of Stockholm (Sweden) suggested there are seven local natural components, of which street trees were listed first (Per Bolund and Hunhammar 1999). The other six include lawns and parks, urban forests, cultivated lands, wetlands, lakes and seas, and streams.

Street tree assemblages are the foundational natural component in the city because street trees can be ubiquitous, provided there exist roadway networks (Berland and Hopton 2014). Although tree-lined streets account for a relatively small fraction of the total area covered by natural components in urban settings, they provide important ecosystem services for urban inhabitants (Mullaney et al. 2015, McPherson et al. 2016). Street trees enhance the urban environment in multiple ways. They add beauty and ornamentation to the built environment (Silvera Seamans 2013), but also provide the benefits of air purification, storm water control, energy conservation, noise reduction, carbon storage, and shade (Silvera Seamans 2013, Mullaney et al. 2015).

The spatial distribution of street tree assemblages within cities is typically non-uniform and is influenced primarily by socio-economic, rather than natural factors (Pham et al. 2017), except in cases where the physical geography is heterogenous (Lowry et al. 2011, Berland et al. 2015). In general, the factors related to socio-economic development can be divided into three categories: 1) urban form (e.g., population density and urban morphology), 2) urban geography (e.g., urban sprawl), and 3) drivers of vegetation management (e.g., public policy, life style). According to the “population density” theory, higher population density leads to less physical space available for vegetation. Indeed, some researchers have found a negative relationship between population density and vegetation cover (Mennis 2006, Conway and Hackworth 2007, Troy et al. 2007, Luck et al. 2009). Recently, however, Bigsby et al. (2013) found positive relationship between human density and tree cover when they compared the cities of Baltimore and Raleigh (USA). Pham et al. (2017) found a negative relationship between total tree cover and population density, but a positive correlation between street tree cover and population density. This finding may reflect changes associated with recent socio-economic development. More research about the relationship between vegetation cover and population density is required to further test the validity of the “population density” theory. Beyond the simple relation between vegetation cover and human numbers, further work is required to explore the spatial distribution of urban tree cover, especially as related to the ecosystem services provided by the vegetation, because we want to know whether the needs of people are being met.

The distribution of natural components in urban settings is also affected by spatio-temporal variations (Howe et al. 2017, Malkinson et al. 2018, Xing et al. 2018). In general, because of high human densities in the urban core relative to suburban areas, the characteristics of natural components in the urban core area are more severely disturbed than in suburban areas (Ren et al. 2012, Ossola and Hopton 2018). It has also been shown that the degree of fragmentation of green space increases along the suburban-urban gradient (Shrestha et al. 2012, Inostroza et al. 2013, Malkinson et al. 2018), and the proportional area of green space displays a decreasing trend with urbanization (Berland 2012). Berland and Hopton (2014), however, found that street tree assemblages do not change significantly along the suburban-urban gradient. They inferred that management practices are more important drivers of street tree characteristics than is urban form.

As a natural component in cities, urban trees are profoundly affected by human policies. How such policies affect urbanization or urban tree cover, however, is not fully understood (Wu 2014). Some research indicates that policies can promote an increase in urban tree canopy cover (Berland and Hopton 2014, Krafft and Fryd 2016). Galenieks (2017), however, in a comparative study of the California (USA) cities of Loma Linda and Redlands, suggested that policies do not always lead to positive effects on urban trees, if commitments to preservation and sound management principles are not fulfilled. Hill et al. (2010) found that some policies improve the status of urban trees, whereas others do not, even though all such policies are presumably initiated to improve planning and tree conservation. More research on urban forest management and the relation between urban forest benefits and existing policies (e.g. city planning policy, climate change adaptation, energy policy) are needed (Krajter Ostoić and Konijnendijk van den Bosch 2015).

In this study, we examined one ecosystem service (air purification) provided by street tree assemblages at the sub-district scale in Shenyang, China, and explored its relationship with human population density, urban sprawl and public policy. We addressed the following questions: (1) does the benefit of street tree assemblages vary as a function of human population density? (2) does the benefit of street tree assemblages vary along a suburban-urban gradient? (3) Does public policy have an effect on the street tree benefit? Our objective was to improve our understanding of how an ecosystem service provided by street trees varies throughout Shenyang, and how urban form and geography influence the spatial distribution of ecosystem services. We also sought to better understand how humans have modified a natural component of this urban environment, and how public policy relates to the ecosystem services provided by street tree assemblages.

2 Study Area And Methods

2.1 Study area

We carried out this study in metropolitan Shenyang, Liaoning Province, northeast China (41^{o}11'51" ~ 43^{o}02'13"N,122^{o}25'09" ~ 123^{o}48'24"E, Fig. 1A). Shenyang is the capital city of Liaoning Province and has an estimated population of 5,864,912 inhabitants (Chinese Census Bureau, 2017). The built, urban area of Shenyang covers about 759 km^2. Shenyang is an inland city with a mean altitude of 51 masl, and is located in the temperate, semi-humid continental climate zone. Average annual temperature and precipitation are 8.6°C and 722 mm, respectively. There are seven districts and 76 sub-districts within the third beltway of Shenyang (Fig. 1B).

2.2 Methods

Field data collection and modelling

We obtained road data, including data on highways and smaller streets, from Google Maps, using ArcGIS 9.3. Field data were collected from June to September 2017. Six percent of all street segments were included during data collection for each sub-district, in accordance with the *I-Tree Street User Manual*, which requires that sample inventories include 3–6% of all street segments to achieve a standard error of ~ 10%. Street segments were randomly selected from the road data set from each sub-district. For each tree, the main attributes we collected were DBH (diameter at breast height), crown size, health condition, LandUse and LocSite which were asked for i-tree street to assess air purification.

Modelling air purification

The i-Tree Streets Model (i-Tree, 2018) was used to assess air purification benefits in metropolitan Shenyang. We first used the method proposed by McPherson (2010) to select the best city match, i.e. to pick a “best fit” climate zone for this Asian city. The best match city for Shenyang was Queens, New York, so the “US northeast climate zone” was chosen for the modelling. To exam the effects of population density, city sprawl (urban-suburban gradient) and district development plans, i.e. government policy on the distribution of air purification ecosystem services provided by street tree assemblages, we regrouped the field data of sub-districts in 3 ways: (1) by population density (districts with population density > 10,000 persons/km^2 were grouped as P1, districts with 1,000–10,000 persons/km^2 were assigned to P2, and districts with < 1,000 persons/km^2 were placed in group P3), (2) by beltways (sub-districts within the first beltway were grouped as B1, sub-districts between the first and the second beltway were assigned to B2, and the sub-districts between the second and the third beltway were places in B3 (Figs. 1B and 1C), (3) by districts (the districts named HG, HP, S, T, Y, HN and D respectively). We got 13 groups in total. We then ran the i-Tree Street Model on each group of field data, individually and got average tree benefit of air purification (ATB, $/tree) and total benefit of air purification for each group.

Statistical analysis

The indices used in this paper are per kilometer benefit (PKB, $/km) and average tree benefit (ATB, $/tree), which indicate the ability of street tree assemblages and individual street trees, respectively, to provide air purification ecosystem services in a specified group. We used PKB instead of the total air purification ecosystem services value of a specified group, because the total length of roads in each group differed, and PKB which is normalized for distance, enables meaningful comparisons between groups.

The one-way ANOVA (LSD was used for pairwise comparisons) was carried out in SPSS 18.0 to analyze how the population density (group P1, P2 and P3), city sprawl (group B1, B2 and B3) and district development plans (group HG, HP, S, T, HN and D) affect air purification ecosystem services, respectively.

3 Results

3.1 Influence of population density

The per kilometer (PKB) and average tree air (ATB) purification benefit for P1, P2 and P3 were, in USD, $1099 and $5.7, $1454 and $6.6, and $1010 and 5.6, respectively (Fig. 2A). There was no significant difference with respect to PKB or ATB when sub-districts were divided into the three population-density groups (Figs. 2A1 and 2A2). When the high- (P1) and low-population (P3) density groups were combined, however, there was a significant difference between the mixed group (high and low) and the group with intermediate population density, P2 (Figs. 2A3 and 2A4). The group with intermediate population density (1000-10,000) displayed a higher air purification benefit for both PKB and ATB. This result is at odds with the “population density” theory.

3.2 Analysis along the urban-suburban gradient

The PKB values of B1, B2 and B3 are, in USD, $1290, $1312 and $941, respectively, and the ATB values of B1, B2 and B3 are $5.8, $6.5 and $5.5, respectively. No statistical difference was found among the three regions when sub-districts were grouped by geographic location, i.e. with respect to beltway position (Fig. 2B).

3.3 Analysis among districts

We found significant differences among districts for the index PKB (Fig. 2C). District T had the highest PKB value, $1403, among the seven districts analyzed (Fig. 2C), and its PKB value is significantly different from that calculated for most of the other districts (Table 1). District T was famous as an old, heavy industry area in China, but urban renewal has been ongoing since 2002. The government has invested heavily in this redevelopment project. Districts HN and S had the lowest PKB values among the seven districts, at $688 and $820, respectively (Fig. 2C). District HN is the newest among the study districts and was organized in 2014. District S is the oldest district of Shenyang, and is a political, economic, cultural and education center. District HP had the second highest PKB value among the seven districts, at $1404 (Fig. 2C). District HP is the second oldest district in Shenyang, but it is the new political, economic, cultural and education center, taking replacing District S in that capacity. Districts D, HG and Y had similar PKB values, around the mean value of $1163 ($1191, $1118 and $1204, respectively, Fig. 2C). District D developed since 2003 for modern manufacturing, the service industry and real estate. District HG is the third oldest district and the education center of Shenyang. District Y is a new district that began to develop modern agriculture and industries in 2010.

4 Discussion

4.1 Street tree air purification benefit and population density

Our findings are at odds with the “population density” theory, and differ from the results of Bigsby et al. (2013) and Pham et al. (2017), who found a trend of increasing street tree cover with greater population density. Our results display no trend between street tree air purification benefit and population density. Highest benefit was not seen in the areas of highest or lowest population density, but rather, in the area of intermediate population density. PKB values in areas of the highest and lowest population density were not statistically different. Luck et al. (2009) also found that highest tree cover occurred in areas with intermediate population density. But they also found that tree cover at the lowest population density was higher than cover at the highest density. The “population density” theory is not supported in many cases. This is probably because the relationship between population distribution and green space is complex. For instance, improved environmental consciousness can lead to more investment in green space construction in old towns where population densities are high (Harrington and Hsu 2018). Furthermore, urban areas may differ with respect to the characteristics of their natural components (Per Bolund and Hunhammar 1999). Changes in the area occupied by the original green space in a city might be explained by the “population density” theory (Ren et al. 2012), whereas the areas covered by artificial green spaces might be explained by other factors (Pham et al. 2017). In theory, areas of lowest population density would have more space available for trees. In our case, however, low population density is associated with low economic development. We suspect that explains why there is lower street tree benefit in the area of low population density than in the area of intermediate population density. Street tree assemblages are different from other conserved green spaces such as parks, which are based on original green spaces. A street tree assemblage is a natural element, but is introduced artificially and related to road development, which, in turn, is related to economic development. Therefore, development of street tree assemblages is dependent on government investment in the construction of roads and their related infrastructure.

4.2 Street tree air purification benefit and urban geography

In most cases, trees/green spaces increase along the urban-suburban gradient (Berland 2012, Ren et al. 2012, Malkinson et al. 2018), but in our case, neither PKB nor ATB is significantly different along the urban-suburban continuum. Berland and Hopton (2014) found the same result in their study. The authors suggested that a time-lag effect related to newly planted trees was not important in their study because even the outer-ring area was more than 40 years old on average. They concluded that management practices such as tree planting were the main drivers of street tree characteristics, and more important than urban geography in their case. We think it is true in Shenyang, too. The area between the second beltway and the third beltway began to be developed about 2004. Most of the street trees are quick-growing species such as aspen and willow. They generally need just seven to fifteen years to develop from seedlings to mature trees in Shenyang. If all areas within the different beltways contain mature trees, the time-lag effect for growth, is inconsequential, and differences among the areas within the different beltways are not significant. Nevertheless, when examining the effect of urban geography, specifically urban sprawl, on street tree ecosystem services, the time scale may be important and should be considered.

4.3 *Street tree air purification benefit and public policy*

Public policy is probably a main driver of vegetation management. Irga et al. (2017) pointed out that policy could encourage green infrastructure installation in Australia. Harrington and Hsu (2018) also showed that policy could take a lead role in driving green infrastructure installation in the US. Our results support this claim. Shenyang began to redevelop old industrial areas (district T) and develop new industries in selected areas (districts D and Y) since 2002, and district T is the key area for the whole plan, as it is held up as a demonstration area. City planning for the old and new industrial areas at that time would have aimed to improve the environment and redevelop old industrial areas as living spaces to attract more citizens to settle there. Green infrastructure construction is an important means to achieve the redevelopment target, and therefore, it is likely that the government would have taken political and economic actions to promote green infrastructure construction in these areas. Hopkins et al. (2018) pointed out that policies that integrate green infrastructure into development plans can lead to improved green infrastructure installation. Government can play a key role in promoting green infrastructure installation and improving ecosystem services in the city. In other words, if the government does nothing on behalf of green infrastructure construction, such as taking no action to improve it, or failing to prevent it from being occupied by a building or some other structure, green space in the city will degrade or shrink (McWilliam et al. 2015).

5 Conclusions

The distribution of air purification benefit provided by street tree assemblages cannot always be explained by the "population density" theory. In Shenyang, China, the district selected by the government to be the key area for development had the highest street tree benefit. This is probably because of the socio-economic aspects of street trees. Street tree installation is related to road construction, which is, in turn, related to economic development. Therefore, where the government invests more for economic development and streets/roads, and promotes local human settlement, there are more street trees and associated air purification benefits. From the ecosystem services perspective, it is good to have more ecosystem services where there are more people. Street tree assemblages, however, are just one natural component in cities. We need further research to elucidate the distribution patterns and factors that affect other natural components and their associated ecosystem services in cities. With that information, we can promote green infrastructure installation to meet the needs of city dwellers.

Public policy is a main driver of street tree plantings and government takes a lead role in promoting street tree installation. Therefore, it is important for the sustainable development of cities that public policy makers be "eco-conscious" when they make decisions. The power of environmental decision-makers in government should be strengthened.

The fact that we detected no difference in street tree assemblage benefits along the urban-suburban continuum is probably a consequence of a time-scale (lag) problem. When the effects of urban sprawl on ecosystem services provided by street tree assemblages are examined, the dynamic variations of street tree assemblages through time should be considered.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Yes

Availability of data and materials

We will share the data if the manuscript is accepted. And we will provide the data if the reviewer requires.

Competing interests

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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Authors' contributions

Jing Yao, conceived and wrote the manuscript

Wei Chen and Miao Liu, main contributors of manuscript conceiving.

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References

1. Berland, A. 2012. Long-term urbanization effects on tree canopy cover along an urban–rural gradient. Urban Ecosystems **15**:721-738.
2. Berland, A. and M. E. Hopton. 2014. Comparing street tree assemblages and associated stormwater benefits among communities in metropolitan Cincinnati, Ohio, USA. Urban Forestry & Urban Greening **13**:734-741.
3. Berland, A., K. Schwarz, D. Herrmann, and M. E. Hopton. 2015. How environmental justice patterns are shaped by place: terrain and tree canopy in Cininnati, Ohio, USA. Cities and the Environment **8**:1-15.
4. Bigsby, K. M., M. R. McHale, and G. R. Hess. 2013. Urban Morphology Drives the Homogenization of Tree Cover in Baltimore, MD, and Raleigh, NC. Ecosystems **17**:212-227.
5. Conway, T. and J. Hackworth. 2007. Urban pattern and land cover variation in the greater Toronto area. The canadian Geographer **51**.
6. Galenieks, A. 2017. Importance of urban street tree policies: A Comparison of neighbouring Southern California cities. Urban Forestry & Urban Greening **22**:105-110.
7. Harrington, E. and D. Hsu. 2018. Roles for government and other sectors in the governance of green infrastructure in the U.S. Environmental Science & Policy **88**:104-115.
8. Hill, E., J. H. Dorfman, and E. Kramer. 2010. Evaluating the impact of government land use policies on tree canopy coverage. Land Use Policy **27**:407-414.
9. Hopkins, K. G., N. B. Grimm, and A. M. York. 2018. Influence of governance structure on green stormwater infrastructure investment. Environmental Science & Policy **84**:124-133.
10. Howe, D. A., J. M. Hathaway, K. N. Ellis, and L. R. Mason. 2017. Spatial and temporal variability of air temperature across urban neighborhoods with varying amounts of tree canopy. Urban Forestry & Urban Greening **27**:109-116.
11. Inostroza, L., R. Baur, and E. Csaplovics. 2013. Urban sprawl and fragmentation in Latin America: a dynamic quantification and characterization of spatial patterns. J Environ Manage **115**:87-97.
12. Irga, P. J., J. T. Braun, A. N. J. Douglas, T. Pettit, S. Fujiwara, M. D. Burchett, and F. R. Torpy. 2017. The distribution of green walls and green roofs throughout Australia: Do policy instruments influence the frequency of projects? Urban Forestry & Urban Greening **24**:164-174.
13. Krafft, J. and O. Fryd. 2016. Spatiotemporal patterns of tree canopy cover and socioeconomics in Melbourne. Urban Forestry & Urban Greening **15**:45-52.

14. Krajter Ostoić, S. and C. C. Konijnendijk van den Bosch. 2015. Exploring global scientific discourses on urban forestry. Urban Forestry & Urban Greening **14**:129-138.
15. Lowry, J. H., M. E. Baker, and R. D. Ramsey. 2011. Determinants of urban tree canopy in residential neighborhoods: Household characteristics, urban form, and the geophysical landscape. Urban Ecosystems **15**:247-266.
16. Luck, G. W., L. T. Smallbone, and R. O'Brien. 2009. Socio-Economics and Vegetation Change in Urban Ecosystems: Patterns in Space and Time. Ecosystems **12**:604-620.
17. Malkinson, D., D. Kopel, and L. Wittenberg. 2018. From rural-urban gradients to patch – matrix frameworks: Plant diversity patterns in urban landscapes. Landscape and Urban Planning **169**:260-268.
18. McPherson, E. G. 2010. Selecting reference cities for i-Tree Streets. Arboriculture & Urban Forestry **36**:230-240.
19. McPherson, E. G., N. van Doorn, and J. de Goede. 2016. Structure, function and value of street trees in California, USA. Urban Forestry & Urban Greening **17**:104-115.
20. McWilliam, W., R. Brown, P. Eagles, and M. Seasons. 2015. Evaluation of planning policy for protecting green infrastructure from loss and degradation due to residential encroachment. Land Use Policy **47**:459-467.
21. Mennis, J. 2006. Socioeconomic-vegetation relationships in urban, residential land: the case of denver, Colorado. Photogrammetric Engineering & Remote Sensing **72**:911-921.
22. Mullaney, J., T. Lucke, and S. J. Trueman. 2015. A review of benefits and challenges in growing street trees in paved urban environments. Landscape and Urban Planning **134**:157-166.
23. Ossola, A. and M. E. Hopton. 2018. Measuring urban tree loss dynamics across residential landscapes. Sci Total Environ **612**:940-949.
24. Per Bolund and S. Hunhammar. 1999. Ecosystem services in urban areas. Ecological Economics **29**:293-301.
25. Pham, T.-T.-H., P. Apparicio, S. Landry, and J. Lewnard. 2017. Disentangling the effects of urban form and socio-demographic context on street tree cover: A multi-level analysis from Montréal. Landscape and Urban Planning **157**:422-433.
26. Ren, Y., J. Yan, X. Wei, Y. Wang, Y. Yang, L. Hua, Y. Xiong, X. Niu, and X. Song. 2012. Effects of rapid urban sprawl on urban forest carbon stocks: integrating remotely sensed, GIS and forest inventory data. J Environ Manage **113**:447-455.
27. Shrestha, M. K., A. M. York, C. G. Boone, and S. Zhang. 2012. Land fragmentation due to rapid urbanization in the Phoenix Metropolitan Area: Analyzing the spatiotemporal patterns and drivers. Applied Geography **32**:522-531.
28. Silvera Seamans, G. 2013. Mainstreaming the environmental benefits of street trees. Urban Forestry & Urban Greening **12**:2-11.

29. Troy, A. R., J. M. Grove, J. P. O'Neil-Dunne, S. T. Pickett, and M. L. Cadenasso. 2007. Predicting opportunities for greening and patterns of vegetation on private urban lands. Environ Manage **40**:394-412.
30. Wu, J. 2014. Urban ecology and sustainability: The state-of-the-science and future directions. Landscape and Urban Planning **125**:209-221.
31. Xing, L., Y. Liu, X. Liu, X. Wei, and Y. Mao. 2018. Spatio-temporal disparity between demand and supply of park green space service in urban area of Wuhan from 2000 to 2014. Habitat International **71**:49-59.

Tables

Due to technical limitations, table 1 is only available as a download in the Supplemental Files section.

Figures

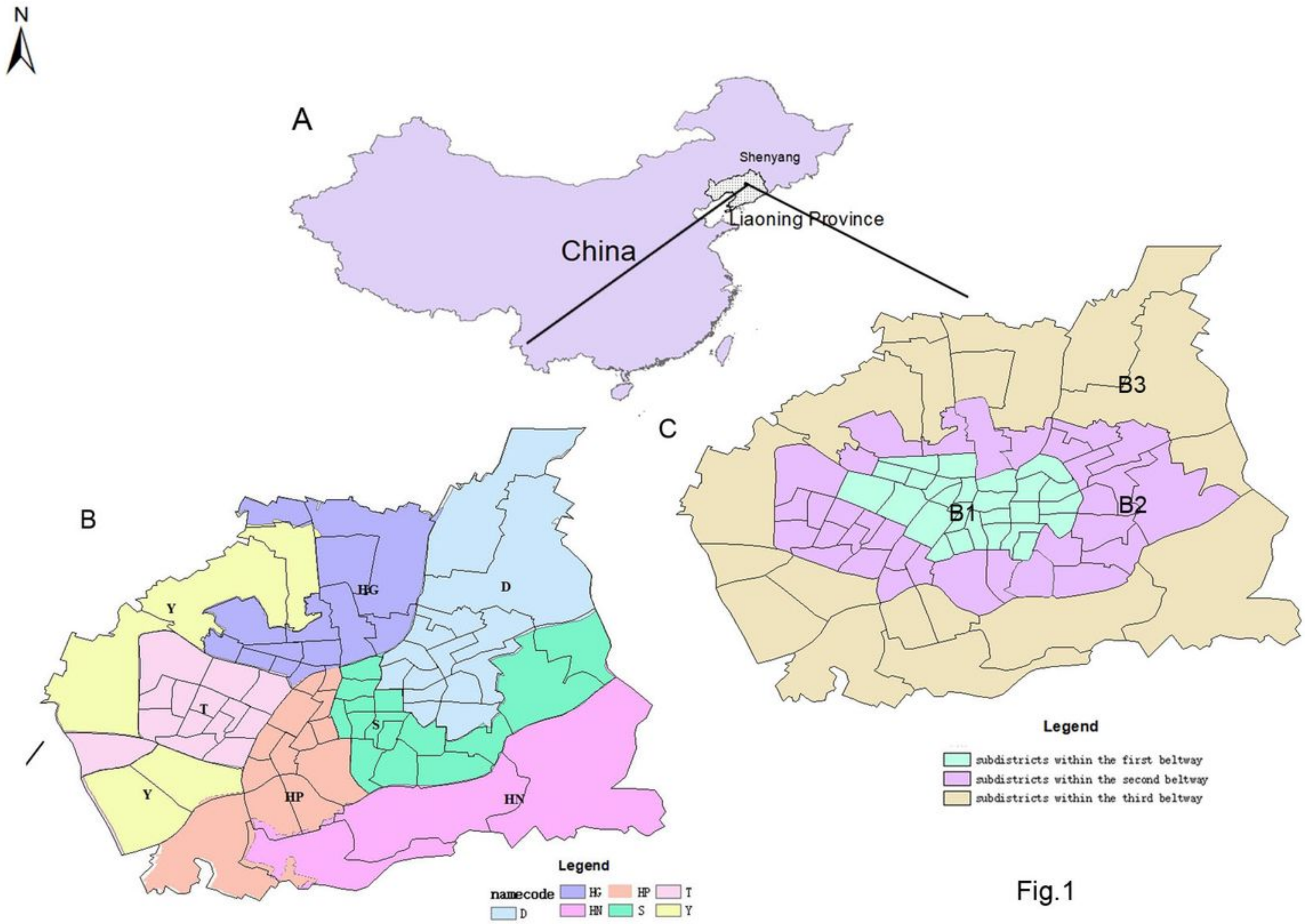

Figure 1

(A) Location of Shenyang in China; (B) Distribution of seven districts and 76 sub-districts within the third beltway of Shenyang; (C) Distribution of 76 sub-districts and the three beltways in Shenyang Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

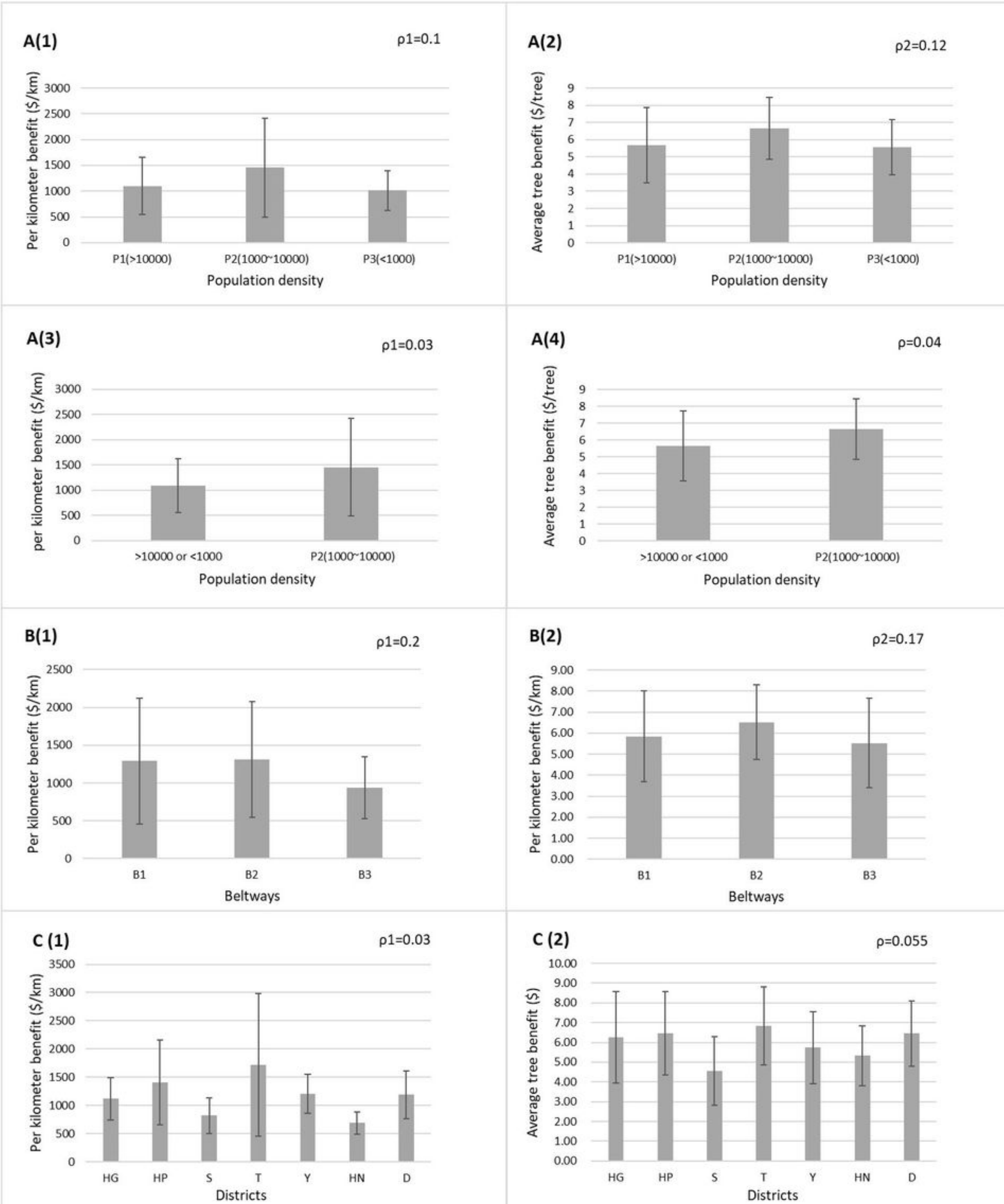

Fig. 2

Figure 2

Comparison of street tree assemblages associated with air purification benefits according to (A) population density, (B) urban-suburban gradient, (C) public policy

Supplementary Files

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- Table1.jpg