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An Investigation of Green Roof Spatial Distribution and Incentive Policies Using Green Buildings as a Benchmark

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Abstract: The global spread of green roofs is becoming increasingly important in the context of increasing urbanization and climate change as they provide multiple benefits, including urban heat island effect (UHI) mitigation, stormwater retention and urban flood risk reduction. However, current research provides little insight into how green roofs are used and promoted globally. Therefore, it is essential to look at the global spatial distribution of green roofs and the related policies by using green buildings which have been successfully promoted as a benchmark. This study collected data from multiple sources, such as a dataset of spatial distribution of green roofs from eight countries, and 124 green roof incentive policy texts from 88 cities. Spatial analysis was conducted using ArcGIS Pro, and different types of incentive policies were explored using word frequency analysis. The results show that (1) the unbalanced distribution of green roofs in cities is prominent, with significant regional differences and clustering characteristics along water systems; (2) in the vast majority of countries, the types of incentive policies for green roofs lack diversity; (3) green roofs lack a well-developed rating system compared to how green buildings are promoted. Combining green buildings with green roofs and exploring the gaps between them, this study will help further explore the application of green roofs worldwide and guide governments or non-governmental organizations to develop and implement more efficient policies and provide recommendations to promote the popularity of green roofs worldwide.

Keywords: green roof; green building; spatial distribution; incentive policy; global review

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1. Introduction

The last few decades have witnessed a rapid growth of population and an increasing level of urbanization; this is continuing in the future, with two-thirds of the world's population living in cities by 2050 [1]. On the other hand, this has been accompanied by various environmental problems, such as the increasing urban heat island effect (UHI) [2–4]. Life-threatening heat waves and concurrent hot and dry summers have been predicted as more common events [5,6]. Urban flooding due to rain events is becoming more widespread and frequent [7,8]. It also leads to health problems and increased energy consumption [9,10]. Nature-based solutions, such as green roofs, are important for optimizing the urban thermal environment while effectively managing stormwater retention and reducing urban flood risk [11,12]. Since there is little remaining useable surface in densely populated cities suitable for conversion to vegetated areas [13], rooftops as undeveloped urban surfaces have the potential to help with climate adaptation and mitigation [14]. Therefore, the promotion of green roofs as an effective green solution is increasingly being valued [15]. The spatial distribution of green roofs in major cities and the policies adopted by countries to incentivize their construction are worthy of investigation so that relevant decisions can be better informed.

Existing research on green roofs in cities has focused on individual building scales, such as the design, technology, and environmental benefits of green roofs [16]. Studies have confirmed that the performance of green roofs depends heavily on their design, such as slope, vegetation intensity, plant coverage, and substrate depth [17–20]. From a technical perspective, studies have recently started to explore the benefits of solutions through the combination of blue-green roofs [21,22], and photovoltaics and green roofs [23,24]. Stormwater retention is one of the most frequently mentioned and intensively studied environmental benefits of green roofs, which can reduce and minimize stormwater runoff by retaining large volumes of stormwater, thereby reducing the risk of flooding [25,26]. Another important environmental benefit of green roofs relates to the roof's thermal performance. Reducing roof temperatures through shading and evaporative cooling can reduce the heat flux into the building, thus reducing heating, ventilation, and air conditioning costs [27,28]. Occasionally, studies have attempted to investigate the environmental benefits of green roofs at the block and community scales [29,30].

To date, however, there have been very few studies of the spatial distribution of green roofs across cities [31,32]. Furthermore, there are few studies on the policies used by different countries to incentivize the construction of green roofs [33,34]. It has been shown that understanding the spatial distribution of green roofs is crucial for incentive policy development [35], and that local government incentives are closely related to the implementation of green roofs. Meanwhile, the potential economic benefits of implementing green roofs at the urban scale can be significant in terms of cost reduction [16]. However, the current small number of studies on the spatial distribution of green roofs and incentive policies at the urban scale missed out many important issues such as the (economic, structural and institutional) barriers associated with green roofs at a broader scale. In this case, effective policy development may be hindered, and it is challenging to provide applicable information for expanding the coverage of green roofs [36].

To fill this gap, this study aims to explore the spatial distribution of green roofs in cities and the characteristics of incentive policies across countries from a global perspective, taking into account geographical and climatic features as well as population and economic levels. The innovation lies in the groundbreaking comparative study using green buildings as the benchmark for green roofs. This is because green roofs and green buildings both are based on buildings and belong to the scale of individual building. Green buildings are better implemented and promoted compared to green roofs [37]. In recent years, a large number of studies have been conducted to explore the differences in spatial distribution and key influencing factors of green buildings [38,39]. However, research findings on the spatial distribution of green roofs are minimal, and quantitative studies using geoinformation technology and spatial statistical methods are lacking. Research on green building incentive policies has been extensively studied by numerous authors from the perspectives of governments, developers, and consumers [40,41], and there are also studies aiming to explore the effects of different types of incentives on green building development [42,43]. On the other hand, green roofs have not been studied in sufficient depth in terms of incentive policies, particularly in the absence of multi-perspective analysis and more profound studies of different types of incentive policies. Therefore, green buildings with abundant research results and more in-depth research can provide more targeted guidance for the implementation and promotion of green roofs. Combining green buildings with green roofs and exploring the gaps in their implementation and promotion will help further explore the spatial distribution characteristics of green roofs at the urban scale to guide governments in formulating and implementing more effective policies.

2. Materials and Methods

2.1. Data Collection and Processing

The main methodological structure of this study is presented in Figure 1. The data were collected from July to September 2022 and pre-processed.

Geographical coordinates and attribute data for exploring the spatial distribution patterns of green roofs were collected by searching online for spatial distribution datasets of green roofs in different cities worldwide and importing them into ArcGIS Pro for spatial analysis. The search terms were "green roof" and "dataset". Overall, eight green roof spatial distribution datasets were collected in this study (Figure 2): (1) San Francisco [44], (2) Chicago [45], (3) New York [46], (4) Toronto [47], (5) London [48], (6) Helsinki [49], (7) Amsterdam [50], and (8) Singapore [51].

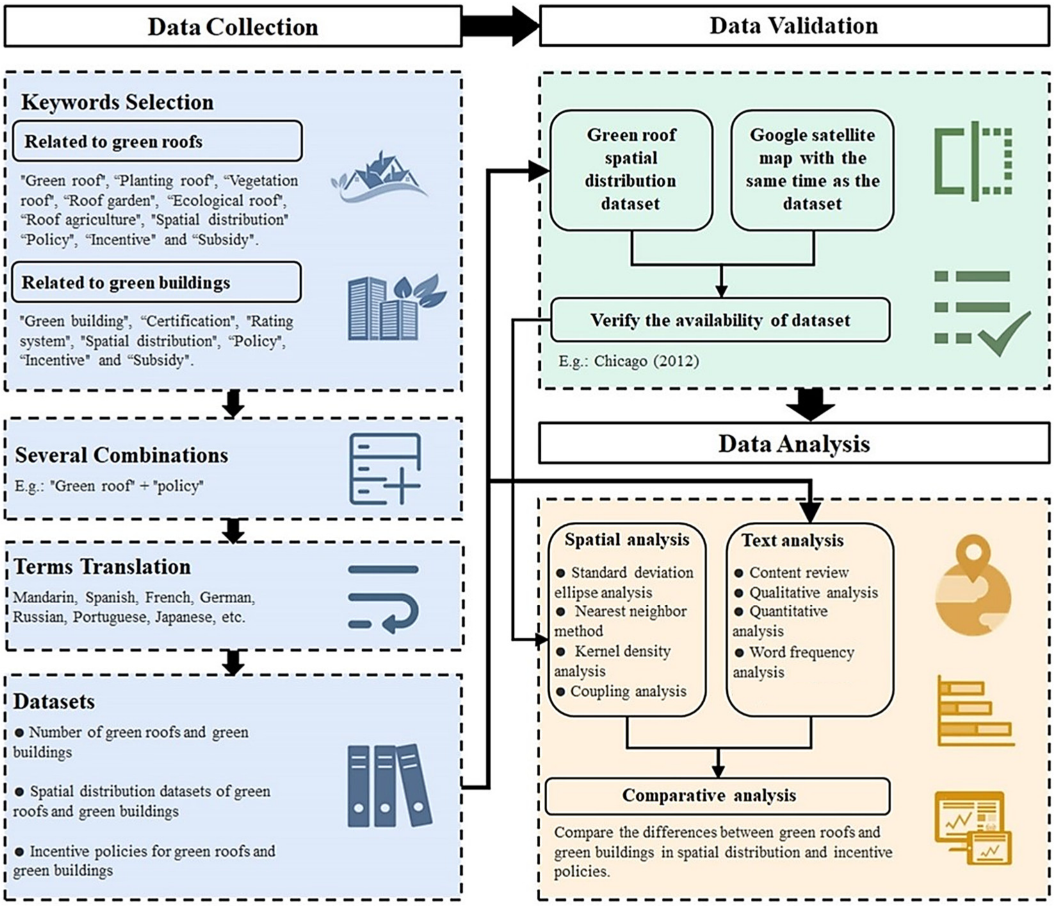
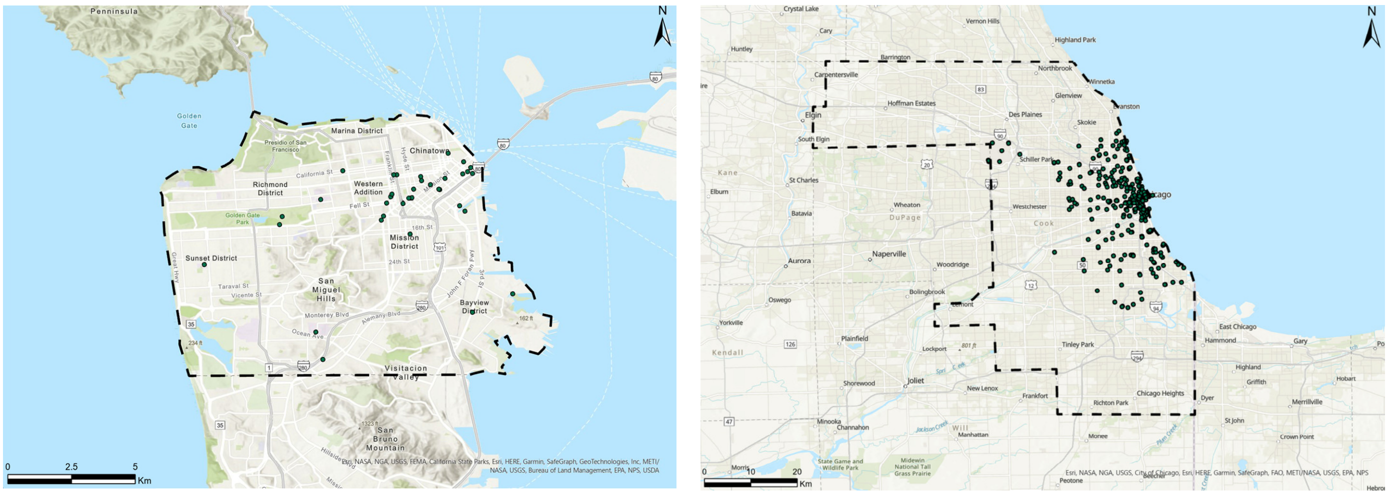


Figure 1. The flowchart of this study.



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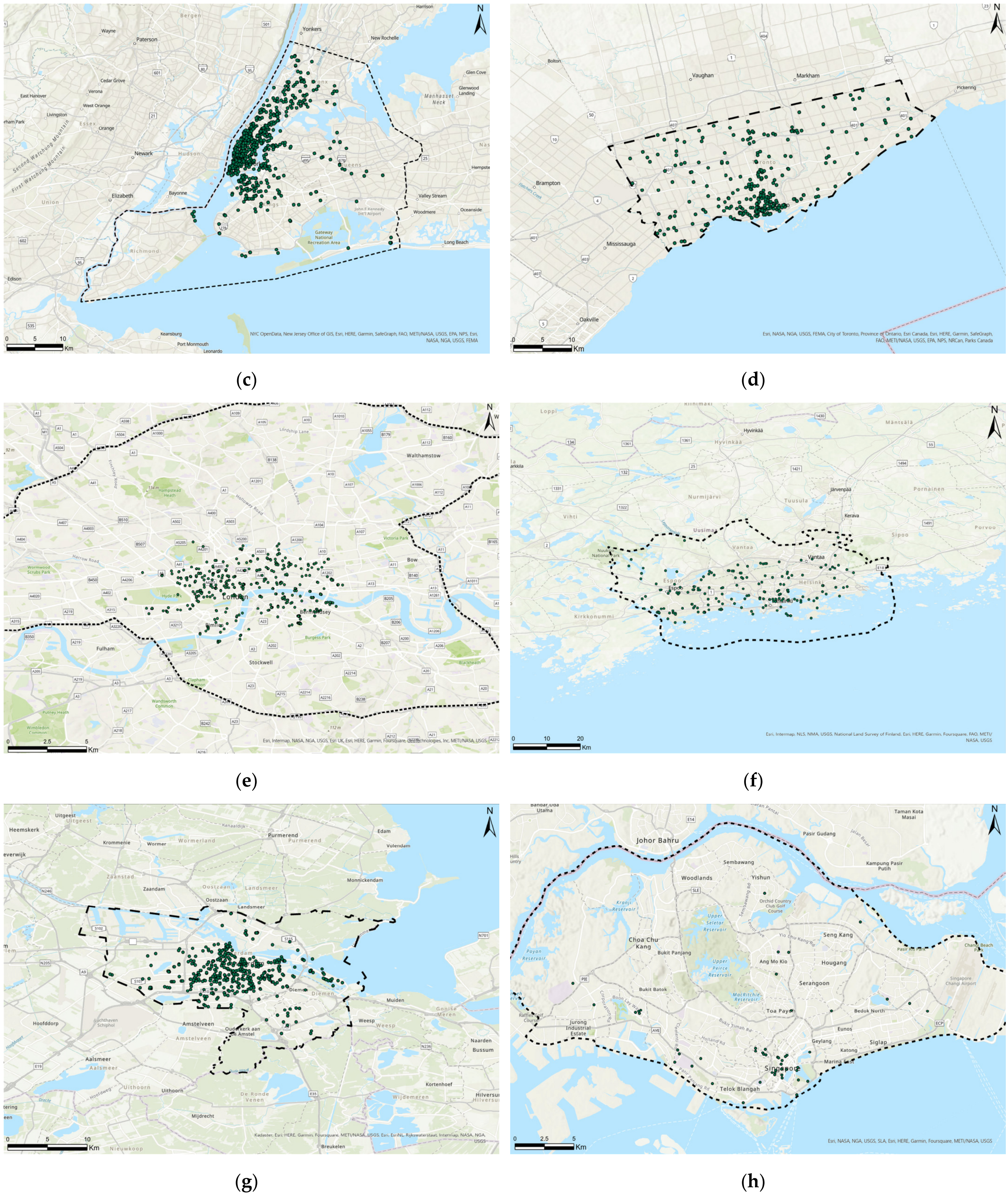


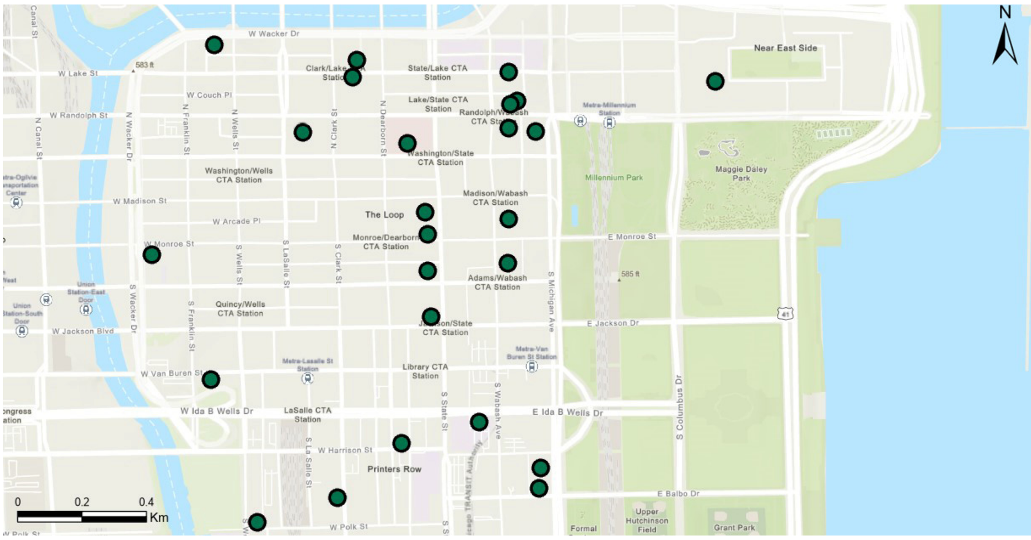
Figure 2. Spatial distribution of green roofs. (**a**) San Francisco; (**b**) Chicago; (**c**) New York; (**d**) Toronto; (**e**) London; (**f**) Helsinki; (**g**) Amsterdam; (**h**) Singapore.

To further explore the characteristics of the spatial distribution pattern of green roofs, a comparative analysis was made between green roofs and green buildings in terms of quantity and spatial distribution pattern. The number and geographic coordinates of green roofs were obtained from the eight green roof spatial distribution datasets mentioned above. Information on the number of green roofs in Washington, Sydney, and Melbourne was obtained from web searches. The information on the number of green buildings was obtained from The Green Building Information Gateway (http://www.gbig.org, accessed on 1 January 2022), where the geographic coordinates of green buildings in San Francisco and New York were obtained from ArcGIS Online (https://www.arcgis.com, accessed on 1 January 2022). To ensure the richness of the data, the green buildings selected for this study were certified by LEED, BREEAM, DGNB, GB Too, Green Mark, Green Star, Green Restaurant Certification, and so on, and the certification dates were up to the last updated date of the dataset.

To collect documents on policies adopted to stimulate the construction of green roofs and green buildings, the search was conducted using Scopus, and official information was obtained from local government websites for text analysis. The authors conducted a web search using the following keywords: "green roof", "planted roof", "vegetated roof", "roof garden", "eco-roof", "rooftop agriculture", "green building" and several combinations of "policy", "incentive", "subsidy", "certification", and "rating system". Different languages were used (such as Portuguese, Spanish, German, Dutch, French, and Chinese). The collected texts were examined to remove those with a low frequency of keyword combinations and to exclude duplicates from the search results. Finally, the search obtained 124 green roof incentives from 5 states, 21 countries, and 88 cities from 1983 to 2023 and 15 green building incentives from 5 countries: Japan, Germany, the United States, Brazil, and Australia.

2.2. Data Validation

The data were validated to ensure the completeness and accuracy (Figure 3). Images were found on Google satellite maps for the year the datasets were created. Then, the images on the satellite maps were compared with the locations of green roof distributions in the datasets for validation. The validation results showed that most of the geographic coordinates of green roofs were accurate, with only a tiny percentage of deviations due to the plants placed on the roofs by the owners themselves. Therefore, the datasets are valid by large and can be used to explore the spatial distribution patterns of green roofs.



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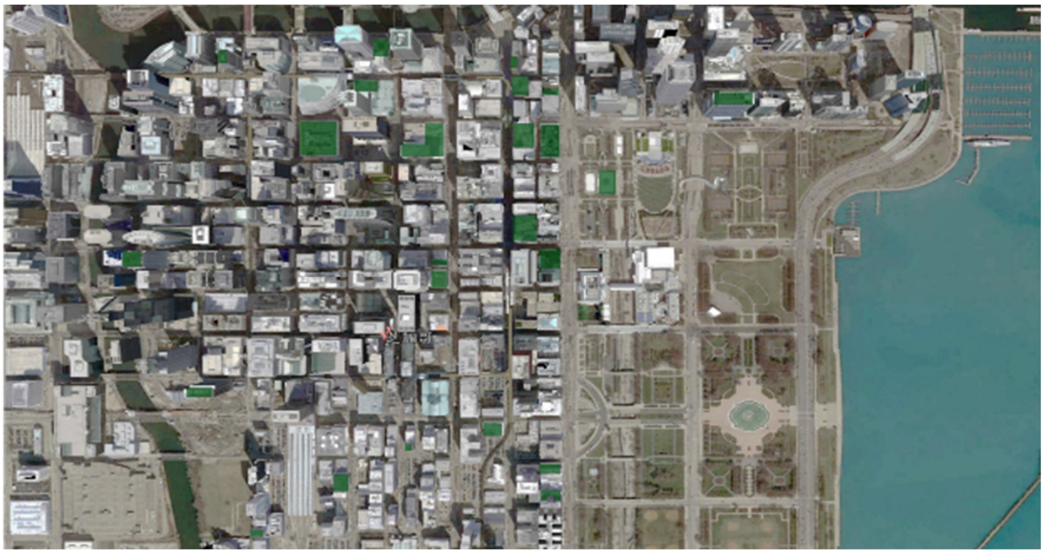


(b)

Figure 3. Data Validation. (**a**) Chicago Green Roof Spatial Dataset (2012); (**b**) Chicago Satellite Map (2012).

2.3. Data Analysis

This study explored the spatial distribution patterns of green roofs using the spatial analysis tool of Geographic Information System (GIS Pro). Eight green roof spatial distribution data, two cities' green building geographic coordinates data and 10 data on the number and geographic location of green roofs and green buildings were used. Standard deviation ellipse analysis was used to describe the spatial distribution direction. The kernel density estimation method was used for spatial uniformity analysis. The nearest neighbor method was used to describe the degree of spatial concentration and verify spatial distribution clustering with statistical significance. Finally, the differences between green roofs and green buildings in terms of number and spatial distribution patterns were compared.

The analysis of incentive policies focused on cities that have incentives to promote green roofs and green buildings. The research defined the categories based on an evaluation of the content of the incentive policies. A quantitative analysis of the timing, region, number, and type of each incentive policy was conducted to compare further the differences in the policies adopted by each country to promote green roofs and green buildings. High-frequency keywords were selected using word frequency analysis to investigate the main directions of mandatory laws and regulations. Finally, the incentive policies for green buildings were used as a benchmark to compare with green roofs in the promotion.

The main incentives used to promote green roofs are divided into eight categories:

1. Mandatory law and regulation: This incentive is a legal requirement that imposes the installation of green roofs in certain new constructions [33]. In Toronto, Canada, for example, all new building projects and all major roof construction projects on both new and old buildings are required to install either a green roof or solar panels on 100% of usable roof space [52];
2. Technical support: This incentive is usually provided by the government to provide guidance on green roofs for owners, constructors and developers [33]. For example, the Growing Green Guide 2014, released in Melbourne, Australia, explains how to create and maintain successful green roofs [52];
3. Density or floor area ratio bonus: This incentive is for landowners that install green roofs [33]. For each square meter of vegetated area, the owner earns permission to build an additional area. For example, Chicago's zoning code in the U.S. awards a Floor-Area Ratio (FAR) bonus for green roofs that cover more than 50% of the roof area [33];

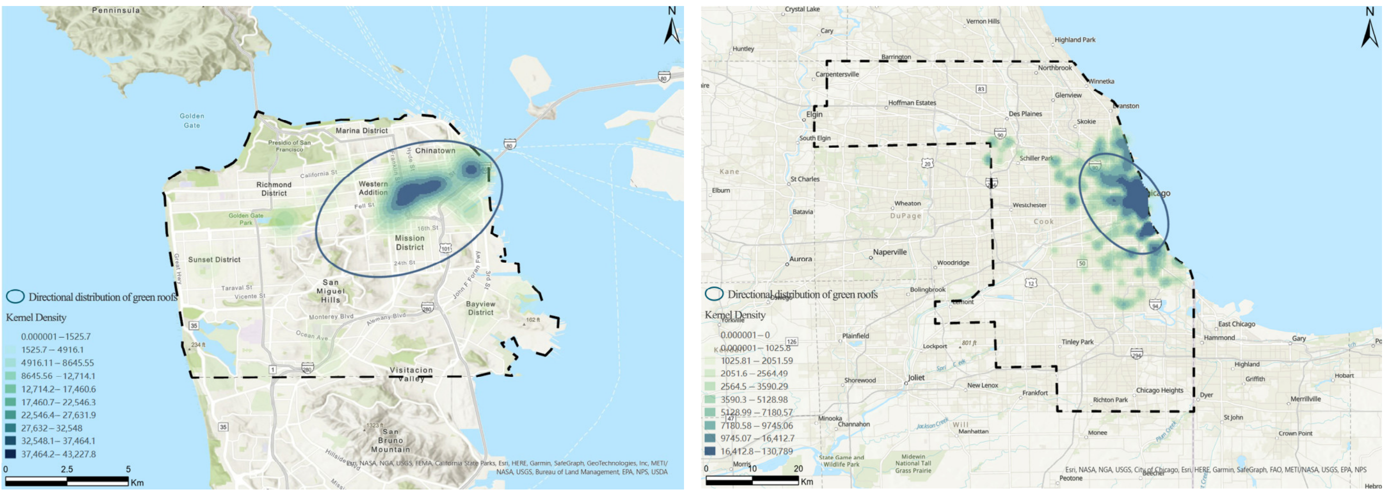
4. Agile management process: This incentive is for projects that include the installation of green infrastructure and receives priority in the licensing process [34]. In Chicago, projects that include green technologies, including green roofs, can receive an expedited permit process (fewer than 30 days) and possibly a reduction in the permit fees [34];
5. Provision of funding (subsidy, grant, rebate, etc.): This incentive is a form of financial aid or supports extended to individuals or companies, which is usually in the form of a cash payment [33]. The City of Basel has promoted green roofs via investment in incentive programs, which provided subsidies for green roof installation [52];
6. Stormwater fee discount: This incentive is a discount to the tax levied according to the impervious surface area for stormwater management [34]. For example, in Ham-burg, Germany, discounts are up to 50% of the annual stormwater fee to landowners with green roofs or other stormwater reduction practices [34];
7. Tax credit: This incentive includes a reduction in property tax and less frequent types of tax reductions, such as in sewage, public lighting, sweeping, and cleaning fees [34]. For example, property owners in New York City can receive a one-year tax abatement of $5.23/square foot for the installation of a green roof, and in certain high-need areas, as much as $15 per square foot [34];
8. Low-interest loan: This incentive is a financial loan with a lower interest rate provided to building owners [34]. In Cologne, Germany, low-interest loans are used to raise state funds for the installation or replacement of green roofs [34].

3. Results

3.1. Spatial Distribution Characteristics of Green Roofs

3.1.1. Overview of the Spatial Distribution of Green Roofs

As shown in Figure 4, a typical characteristic of the spatial distribution direction of green roofs is the dispersed distribution along the water system. The analysis of the standard deviation ellipse shows that the center of gravity of the standard deviation ellipse is apparently close to the water system. The long axes of all eight standard deviation ellipses follow the trend of the water system, which proves that the overall distribution pattern of green roofs is denser along the water system and mostly dispersed along the trend of the water system.



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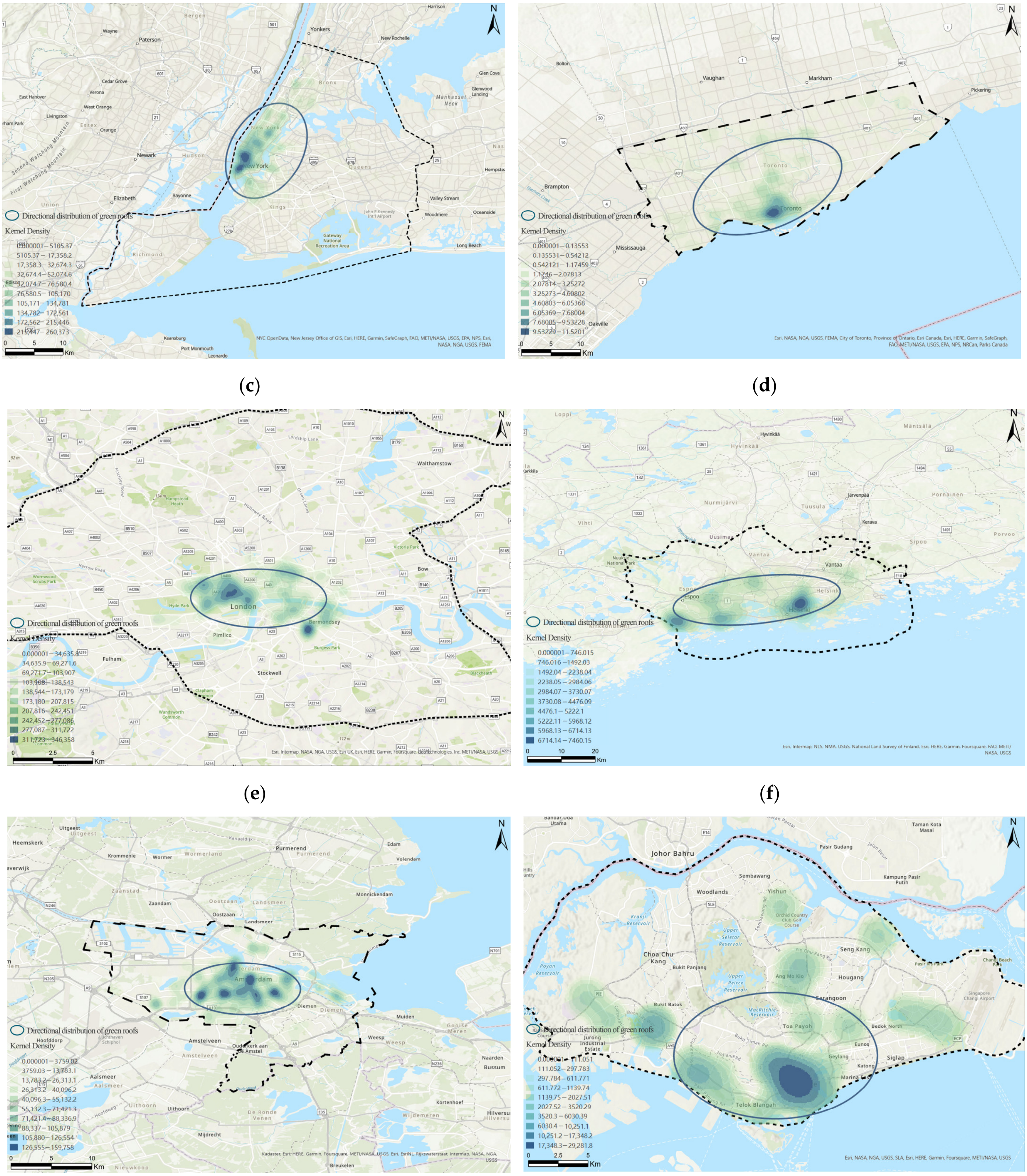


Figure 4. Spatial distribution direction and density of green roofs. (**a**) San Francisco; (**b**) Chicago; (**c**) New York; (**d**) Toronto; (**e**) London; (**f**) Helsinki; (**g**) Amsterdam; (**h**) Singapore.

The density distribution of green roofs is also shown in Figure 4. Kernel density estimates were performed to generate a heatmap with the number of green roofs distributed varying from high to low. The darker color in the plot represents the higher density of green roof distribution. The results show that the city's spatial distribution of green roofs has a core–perimeter structure, showing a highly unbalanced state with significant regional differences. The areas with a higher density of green roof distribution are primarily concentrated along the water system. The number of distributions shows a characteristic of gradual dispersion from the core to the periphery.

In this study, the mean nearest neighbor tool in the spatial statistics of Geographic Information System (GIS pro) was used to calculate the mean distances between each observed point and its nearest neighboring point. Then, the mean was compared with the expected value from the complete spatial randomness (CSR) pattern to obtain the standard deviation (Z-score) [53]. When the z-score is negative and the value is small, the distribution pattern is clustered, while the opposite suggests dispersed [54]. In addition, the nearest neighbor index (*NNI*) can also be used to judge whether the point pattern is clustered or dispersed, which can be calculated using Equation (1):

$$NNI = \frac{\overline{d_{min}}}{E(d_{min})} = \frac{\sum_{i=1}^{n} d_{min}/n}{0.5\sqrt{A/n}} \tag{1}$$

where d_{min} is the distance from each green roof to its nearest neighbor green roofs. $E(d_{min})$ is the expected value of the distance from each green roof to its nearest neighbor green roofs in the random distribution mode. N is the number of green roofs in the region, and A is the study region [55].

If NNI > 1, the distribution pattern is dispersed; NNI ≈ 1, the distribution pattern is random; and NNI < 1, the distribution pattern is clustered [56].

The parameters of the average nearest neighbor analysis are shown in Table 1. The nearest neighbor indexes (NNI) of all eight regions are less than 1 and the Z-scores are all negative, indicating that the spatial distribution of green roofs in these regions shows the characteristics of clustering.

Table 1. Parameters of the average nearest neighbor analysis of green roofs.

Region	Observed Mean Distance (Km)	Expected Mean Distance (Km)	Nearest Neighbor Index	Z-Score	Distributed Pattern
San Francisco	551.54	729.99	0.76	−2.76	Clustering
Chicago	451.50	817.01	0.55	−16.19	Clustering
New York	227.04	557.38	0.41	−30.76	Clustering
Toronto	435.07	713.25	0.61	−14.00	Clustering
London	74.04	167.11	0.44	−23.22	Clustering
Helsinki	608.97	955.76	0.64	−10.34	Clustering
Amsterdam	177.80	324.66	0.55	−18.48	Clustering
Singapore	1047.01	1473.79	0.71	−3.92	Clustering

3.1.2. Comparison of the Spatial Distribution of Green Roofs and Green Buildings

In order to explore the differences between green roofs and green buildings in terms of spatial distribution patterns, the quantity and spatial distribution of the two have been compared using comparative analysis. They are comparable because green roofs are based on buildings where the scale of both is unified. Figure 5 compares green roofs and green buildings in terms of quantity. The results show that the number of green roofs is much less than that of green buildings, and green roofs have not yet achieved the same degree of popularity as green buildings. San Francisco and Singapore are particularly notable for their differences in the number of green roofs and green buildings. The difference in the number of green roofs is less significant in Toronto and Helsinki.

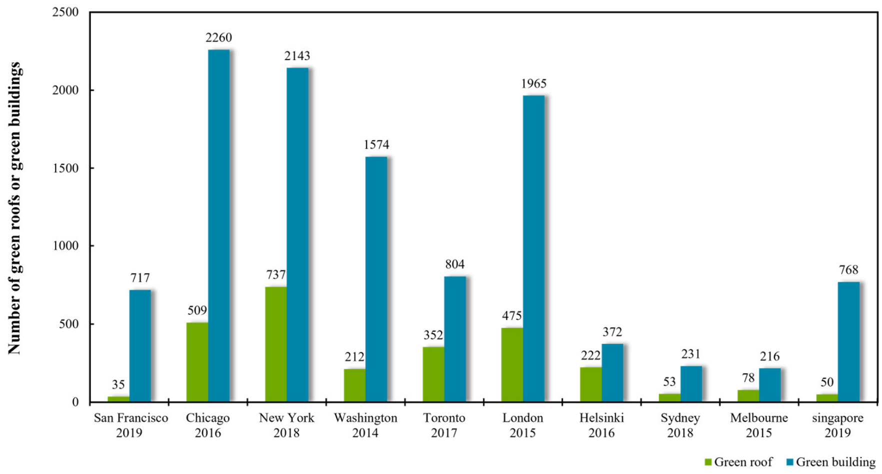
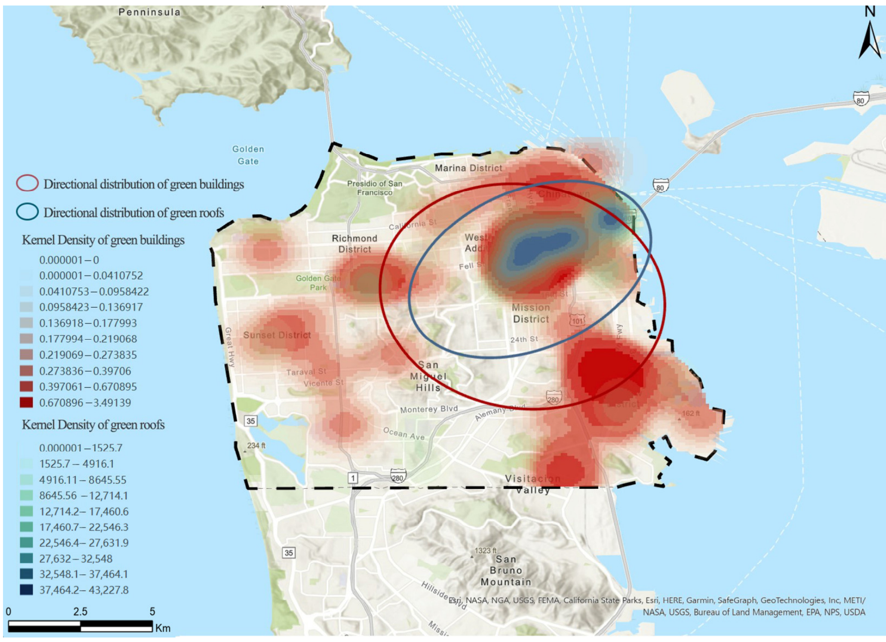


Figure 5. Comparison of the number of green roofs and green buildings in different regions.

The cities of San Francisco and New York are known as one of the exemplary cities for the implementation of green roofs in North America [57]. Therefore, San Francisco and New York were selected for the coupling analysis of the spatial distribution of green roofs and green buildings (Figure 6). The spatial distribution of green roofs and green buildings has a slight overlap and a significant difference in quantity, so the coupling is not significant. There is a core–periphery structure to the city's spatial distribution of green roofs, which shows a clear regional imbalance. In contrast, the city's spatial distribution of green buildings is characterized by a decentralized multi-core layout, showing a more balanced pattern. The spatial distribution of green buildings indicates a more comprehensive range of promotion. Therefore, when the government develops incentive policies related to green roofs, it could refer to how green buildings are promoted in order to develop targeted policies based on the unique situation of different cities. In particular, it needs to focus on the surrounding areas to help them get rid of the backlog of green roof development to promote the popularity of green roofs and achieve a more balanced distribution of green roofs.



(**a**)

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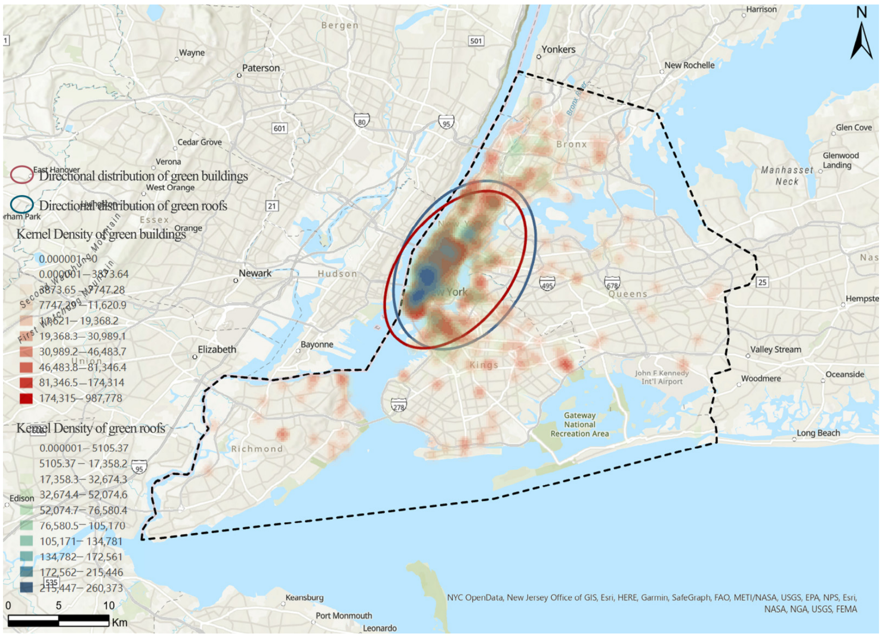

(**b**)

Figure 6. Comparison of spatial distribution between green roofs and green buildings. (**a**) San Francisco; (**b**) New York.

3.2. Incentive Policies for Green Roofs

3.2.1. Overview of Incentive Policies for Green Roofs

In this section, we conducted a content review, qualitative analysis, quantitative analysis, correlation analysis, and word frequency analysis to provide an overview of the policies that incentivize green roofs concerning the timing of their issuance, region, number, type, and content of green roofs. The study includes 88 cities in 21 countries on five continents. A total of 124 different incentive policies were analyzed, as some cities had more than one type. Based on the content of the incentives, the types of green roof incentives were categorized into eight categories: mandatory law and regulation, technical support, density or floor area ratio bonus, agile management process, provision of funding (subsidy, grant, rebate), stormwater fee discount, tax credit, and low-interest loan.

Figure 7 shows the number of different types of incentives on each continent. An important finding is the lack of diversity in the types of incentives in most regions. The two most widely used types of incentives are mandatory law and regulation and provision of funding (subsidy, grant, rebate). Worldwide, Europe and North America issued the largest number of incentives and excelled in providing financial incentives. The incentive of offering a discount on stormwater fees is highly prevalent in North America, which is followed by Europe, and it is not used in other continents. North America has the most variety of incentive policies and agile management processes. Incentives in South America and Oceania focus on measures that do not require direct financial incentives, such as mandatory law and regulation, technical support, and tax credit.

Based on a global perspective, the texts of mandatory law and regulation were analyzed for word frequency, and the three primary financial incentives of providing funding (subsidy, grant, rebate), stormwater fee discount, and tax credit were compared. Among the mandatory law and regulation, "new", "public", "commercial", "office", and "residential" appear with greater frequency. This reflects that the policy applies mainly to new, public, commercial, office, and residential buildings. "Height", "area", "size", "slope", "degree" and "flat" also appear more frequently, which indicates that the implementation of these policies needs to take into account the structural factors of the buildings. Figure 8 shows a comparison of the financial incentives offered by different cities. Most cities provide 50% financial support in terms of funding (subsidy, grant, rebate) and tax credit, with the

United States providing the most generous amount of support (up to 100%). In terms of stormwater fee discounts, Poland offers the highest discounts (up to 100%).

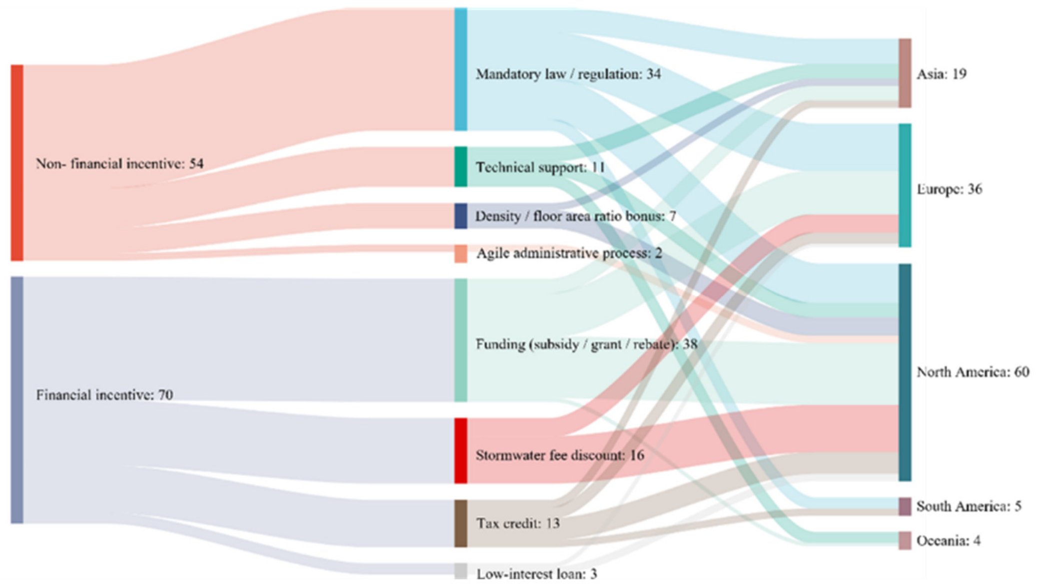

Figure 7. Number of incentives for different types of green roofs.

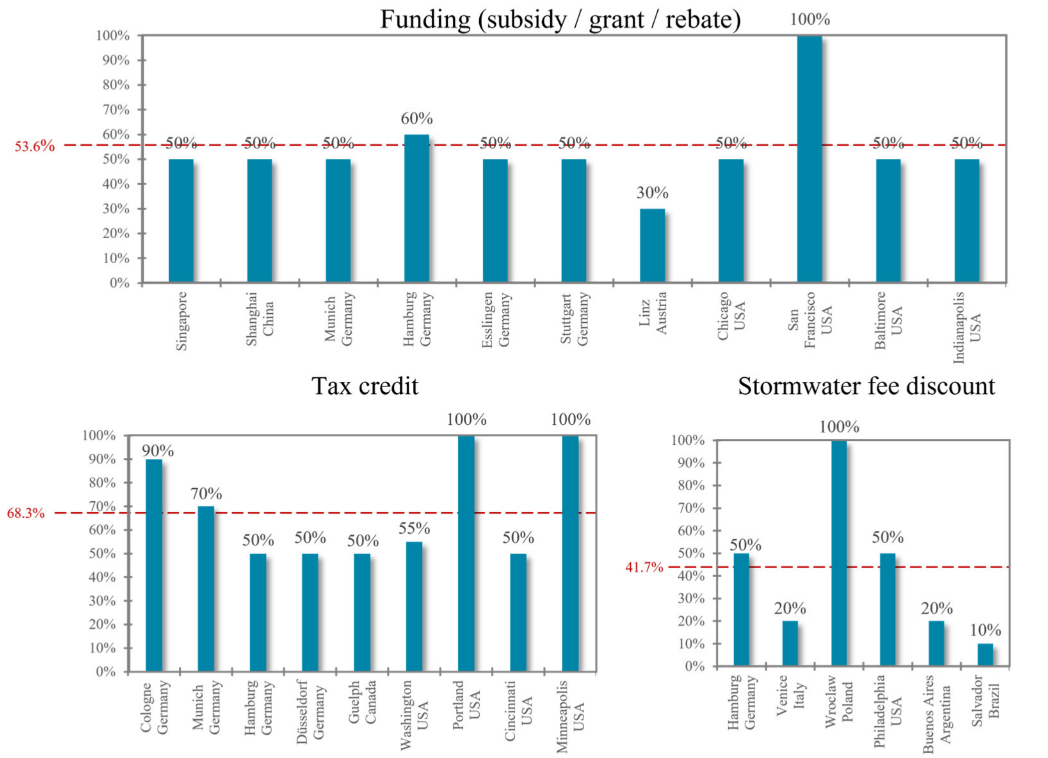

Figure 8. Comparison of financial incentives provided by different cities.

The timing and number of different incentive types issued are shown in Figure 9. The results show that the types of incentives for green roofs have become more diverse since 2005. The two types of incentives, mandatory law and regulation and provision of funding (subsidy, grant, rebate) were the first incentives to be implemented and have remained popular with governmental or non-governmental organizations.

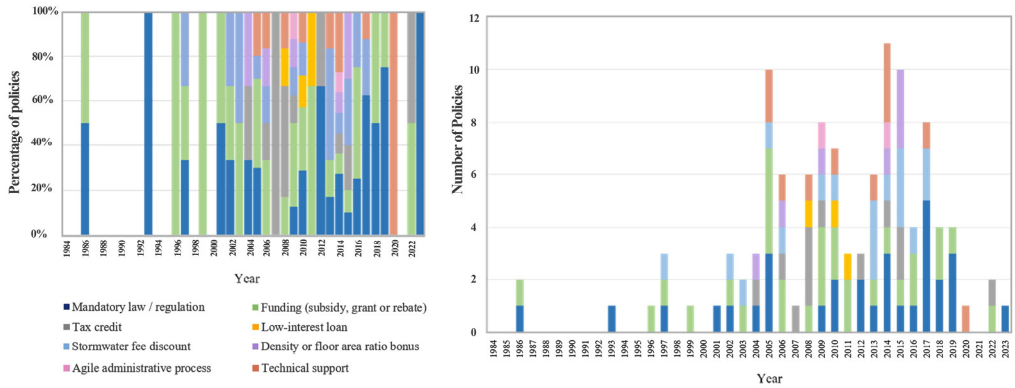

Figure 9. Time and quantity of different types of incentive policies.

Figure 10 shows each country's temporal and spatial distribution of incentive policies. Europe and North America have the highest number of incentive policies globally. Europe was the first to release incentive policies and has a more balanced distribution regarding the time of policy release. After the twenty-first century, North America began releasing incentive policies but had the highest total number of policies released. In Asia and South America, incentives were released at a later date and in smaller numbers. While many cities around the world have implemented green roofs, Oceania has lagged in terms of the latest and lowest number of policies released.

Figure 10. Spatial and temporal distribution of green roof incentive policies.

3.2.2. Comparison of Green Roofs and Green Buildings Incentive Policies

For the five continents, countries with more successful policies for green roof incentives were selected and analyzed compared to green building. Table A1 (Appendix A) compares the mandatory law and regulation for green roofs and green buildings in Japan, Germany, the United States, Brazil, and Australia. The results show that the mandatory law and regulation for green roofs and green buildings in these five countries provide a legal basis for promoting green roofs and green buildings. The difference is that the mandatory law and regulation for green roofs are more focused on the roof (such as area, slope, and vegetation coverage), while green buildings focus on building energy efficiency. This type of incentive is absent from Australia's green roof incentive policy. Japan, Germany, and Brazil have more extensive, mandatory, and stringent green roof and green building legislation and regulations. The mandatory law and regulation in the United States are less mandatory and have more lenient restrictions.

Specific forms of financial incentives are the provision of funding (subsidy, grant, rebate), tax credit, discount on stormwater fee, and low-interest loan. A comparison of financial incentives for green roofs and green buildings in Japan, Germany, the United States, Brazil, and Australia is shown in Table A2 (Appendix A). The results show that Brazil and Australia have a single source of financial incentives and funding to promote green roofs and green buildings, which increases the financial burden. When it comes to a specific implementation, Brazil and Australia also have limited funding targets, narrow coverage, and insufficient incentive to provide financial incentives for a wide range of buildings. These three countries offer the driving force for financial incentives through stormwater fee discount, tax credit, regulation of loan interest, and the involvement of private funds in management through non-governmental organizations.

The rating system also reflects the policy gap between green roofs and green buildings. One of the most critical and fundamental policy tools in various policy frameworks that promote the spread of green buildings is the green building rating system [58]. It has been demonstrated that there is a strong correlation between the rating of green buildings and the spread of green buildings [59]. Green roofs, on the other hand, are lagging in rating systems. Table A3 (Appendix A) compares the assessment or rating systems that incentivize the construction of green roofs with green buildings in Japan, Germany, the United States, Brazil, and Australia. In Japan and Brazil, there is no assessment or rating system for the construction of green roofs. The United States and Australia both use the Green Factor green roof assessment system, and Germany uses the Biotope Area Factor green roof assessment system, both of which are score-based requirements. Both assessment systems require new developments to meet a specified minimum score but do not have a rating system for them. However, in terms of the green building rating systems, all five countries have developed clear rating systems with detailed regulations on the ratings.

4. Discussion

4.1. Interpretation of Results

This study obtained some significant findings by analyzing the spatial distribution patterns and incentive policies of green roofs with green buildings as benchmarks. First, the spatial distribution of green roofs is highly uneven, showing regional variability, clustering characteristic, and spatial distribution direction following the distribution along the water system. One possible explanation is that the current green roof implementation projects are mainly used as demonstration projects to serve as a model for education. For example, green roof demonstration projects have been constructed in Richmond [60]. On the other hand, green building is one of the measures proposed as a universal project to mitigate the building stock's significant environmental, social and economic impacts, and it has been widely implemented in many cities worldwide [61]. Another reason for the uneven spatial distribution of green roofs may be due to the good geographic and climatic conditions along waterways. Regional economies may be more dynamic and more likely to attract higher-income consumers who can afford better-quality roofs and well-educated consumers who prefer green lifestyles. These consumers are more likely to take social responsibility for pursuing a low-carbon environment. Meanwhile, they often have more social capital, which allows them to have a more significant radiating effect on the surrounding area and are more suited as demonstration projects to promote green roofs. Therefore, when formulating incentive policies related to green roofs, the government should focus on the surrounding areas in particular, according to the unique situation of different cities, to help them get rid of the lagging situation of green roof development. The government also needs to popularize green roofs and promote a more balanced and equitable distribution of green roofs to achieve a green and low-carbon life shared by all.

With respect to incentives, Europe and North America have a greater number of incentives, perhaps because the majority of research has been conducted over the last decade in these regions that provided policymakers with a greater understanding of the benefits that can be derived from these actions [62,63].

4.2. Insights

In the coming years, the global increase in population will lead to an increase in urbanized areas, which will bring about an increase in energy demand for buildings and a spike in urban temperatures (i.e., urban heat island effect), which in turn will affect the energy use of buildings [14]. Thus, green roofs deserve widespread popularization as a nature-based solution, since it is often regarded as one of the most suitable sustainable solutions to urban heat island-related issues [64]. Green roofs can also help improve stormwater management, mitigate the urban heat island effect, extend the life of roof membranes, enhance urban aesthetics, create recreational spaces, and save energy for heating and cooling buildings [65]. Large-scale green roof demonstration projects have been built in many countries, and different types of incentives have been adopted to promote the spread of green roofs [34].

One lesson from the spatial distributional characteristics of green roofs is that governments or non-governmental organizations should tailor green roof incentive policies to local circumstances. They should not only focus on demonstration projects but also concentrate on the surrounding areas where green roofs are falling behind in development. It is of great importance to form a more balanced and equitable distribution of green roofs and realize a green and low-carbon life shared by all.

Another lesson is that establishing a green roof rating system may be a key step in promoting the spread of green roofs. Green building rating systems are a fundamental part of a political framework for promoting green buildings in many countries [66,67]. Approximately 600 green rating systems have been developed and applied worldwide [68]. The rating systems for green buildings are evaluated on criteria such as energy, site, indoor environment, land and outdoor environment, materials, water, and innovation [69]. However, different rating systems have different priorities considering climate differences, economic development and social needs [70]. Whereas green roofs only use score-based assessment systems [71–73], they are clearly lagging behind in rating systems, which is not conducive to the spread of green roofs around the world. Therefore, green roofs should learn from green buildings when developing rating systems and should pay attention to the differences between national development (such as population, economy, and system), as well as climate and environment, to set different weights and develop appropriate rating systems.

Based on the above-mentioned differences between green roofs and green buildings in terms of implementation and promotion, this study proposes three policy recommendations to local governments from a planning perspective, using green buildings as a benchmark. Firstly, the government should take active measures to promote green roofs, because their attitude is crucial to implementing green roofs. When green buildings are promoted, many mandatory laws and regulations are established to give baselines for implementing green buildings and guarantee the accomplishment of the goals set by the government [74]. The policy about green roofs can also actively take measures such as mandatory laws and regulations to address the barriers such as the lack of motivation of building stakeholders. In addition, government subsidies should be increased to a certain high level, and appropriate penalties through mandatory regulation could be considered. Government subsidies directly drive green roof adoption among stakeholders [75]. However, green roofs cannot be dependent on subsidies forever. Therefore, the final recommendation is to increase public awareness of the benefits that green roofs offer, and market demand will increase when the public believes that green roofs can reduce carbon emissions and lead to healthy living. Green buildings, for example, were first implemented as demonstration projects on government-funded public buildings [76,77]. Green roofs can also be promoted based on this idea by prioritizing the construction of demonstration projects on government buildings, educational buildings and other building types to raise the awareness and motivation of people in the surrounding areas.

4.3. Limitation

Although the study has some theoretical and practical significance, there are some limitations. First, due to the limitation of data availability, only a preliminary judgment was made in terms of spatial distribution. The specific effects of geography and climate, economy and population density, and so on, were not extensively investigated. Second, selecting only certified green building projects to measure green building development may not be sufficiently accurate. In addition, the study of incentives did not distinguish between different types of green roofs, such as extensive green roofs and intensive green roofs, which need to be thoroughly analyzed in future studies. Finally, although representative cases of spatial distribution and incentive policies were selected for this study, future research suggests using more comprehensive data to verify the generalizability of the findings. Future research can also explore the evolution of the spatial distribution pattern of green roofs and the clustering phenomenon, and it can thoroughly analyze the effectiveness and barriers of various incentive policies from multiple perspectives.

5. Conclusions

In this study, multiple datasets were used to explore the spatial distribution patterns of green roofs and green buildings using the spatial analysis tool of Geographic Information System (GIS Pro). It was found that the distribution of green roofs was highly unbalanced, with noticeable regional differences. In addition, green roofs have clustering characteristics and tend to be distributed along the water system with a core–perimeter structure. The texts of green roof and green building incentives across the world were analyzed in the study. The results found that in the vast majority of cities, there is a lack of diversity in the types of green roof incentives. Two types of incentives, mandatory law and regulation as well as the provision of funding (subsidy, grant, rebate), have been popular with governmental or non-governmental organizations. Learning from how green buildings are promoted, green roofs need a rating system, and the rating criteria should show diversity and regionality.

The findings of the study support the equity of green roof implementation and promotion in cities. In addition, this study helps policymakers, residents, architects, and developers better understand the benefits of green roofs and their applications worldwide. It also provides governmental or non-governmental organizations with references and recommendations for developing incentive policies to accelerate the implementation of green roofs in the global building sector.

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Appendix A

Table A1. Comparison of mandatory laws and regulations encouraging the construction of green roofs and green buildings.

Country	Type	Example	Scope of Application	Restrictions
Japan	Green roof	Nature Conservation Ordinance 2001 Greening areas must be provided on the premises and on rooftops when buildings are newly constructed, repaired or extended to an area larger than 1000 m^2 for private facilities and 250 m^2 for public facilities.	Newly constructed, repaired or extended to an area larger than 1000 m^2 for private facilities and 250 m^2 for public facilities	Area; vegetation coverage
	Green building	Energy Conservation Law 2008 Requirements for greenhouse gas emission reduction, energy saving measures and performance of large buildings, new independent houses and small and medium-sized buildings	large buildings, new independent houses and small and medium-sized buildings	Greenhouse gas emissions; energy efficiency
Germany	Green roof	City of Stuttgart regulation 1986 Requirements for all new roofs below 12 degree slope must have green roofs.	New roofs	Roof slope
	Green building	The Energy Conservation Act 2013 Introduces the obligation of the nearly zero-energy standard for new buildings. This obligation will apply to all new public buildings from 2019 onwards and to all other new buildings as of 2021.	New public buildings from 2019 onwards and to all other new buildings as of 2021	Time; Energy efficiency
the United States of America	Green roof	NYC Local Law 92 & 94 2019 All new building projects and all major roof construction projects on both new and old buildings will be required to install either a green roof or solar panels on 100% of usable roof space.	New buildings; major roof construction projects	Usable roof space
	Green building	The Energy Policy Act 2005 Provide incentive policies for green buildings: full and partial tax deductions for investments in energy efficient commercial building that are designed to increase the efficiency of energy-consuming functions	Energy-efficient commercial buildings	Energy efficiency

Table A1. *Cont.*

Country	Type	Example	Scope of Application	Restrictions
Brazil	Green roof	Green Roof Law 2014 Requires buildings with more than four floors to have their roofs covered with native vegetation. The law also applies to any commercial building with more than 400 square meters.	Buildings with more than four floors; commercial building with more than 400 square meters	Native vegetation
	Green building	Norma Brasileira Regulamentadora15575 2013 Put forward general requirements for residential building performance, such as structural systems, floor systems, wall systems, roofing systems, and hydro-sanitary systems.	Residential building	Performance
Australia	Green roof	None	None	None
	Green building	Building Code of Australia 2019 The office building design is required to meet the requirements of NABERS operating energy consumption of 6 stars. All residential design will meet the 7-star standard of NatHERS software in 2022.	Office buildings; residential buildings	Time; Energy efficiency

Table A2. Comparison of financial incentives encouraging the construction of green roofs and green buildings.

Country	Type	Measures	Source of Funds	Funded Object
Japan	Green roof	Funding (subsidy/grant/rebate); Low-interest loan; Tax credit	National government; local government; non-governmental organizations	All qualified buildings
	Green building	Funding (subsidy/grant/rebate); Tax credit	National government; non-governmental organizations	New residential buildings
Germany	Green roof	Funding (subsidy/grant/rebate); Low-interest loan; Tax credit; Stormwater fee discount	Local government	All qualified buildings
	Green building	Funding (subsidy/grant/rebate); Low-interest loan; Tax credit	National government; non-governmental organizations	All qualified buildings

Table A2. *Cont.*

Country	Type	Measures	Source of Funds	Funded Object
the United States of America	Green roof	Funding (subsidy/grant/rebate); Low-interest loan; Tax credit; Stormwater fee discount;	Local government; non-governmental organizations	All qualified buildings
	Green building	Funding (subsidy/grant/rebate); Low-interest loan; Tax credit	National government; local government; non-governmental organizations	Commercial buildings, new residential buildings, new technologies and demonstration projects
Brazil	Green roof	Tax credit	Local government,	New developments, extensions and renovations of existing buildings
	Green building	Tax credit	Local government,	New residential buildings
Australia	Green roof	Funding (subsidy/grant/rebate)	Non-governmental organizations	Sustainable development projects
	Green building	Funding (subsidy/grant/rebate); Tax credit	Non-governmental organizations	Residential buildings, commercial buildings, office buildings, primary and secondary schools, hotels, shopping centers and other types of buildings that can be evaluated by NABERS

Table A3. Comparison of assessment or rating systems encouraging the construction of green roofs and green buildings.

Country	Type	System	Content	Rating
Japan	Green roof	None	None	None
	Green building	CASBEE (New Construction 2014)	Environmental Quality of Building Indoor Environment Quality of Service Outdoor Environment Environmental Load Reduction in Building Energy Resources and Materials Off-site Environment	Excellent; Very Good; Good; Fairy Poor; Poor
Germany	Green roof	Biotope Area Factor (BAF).	Safeguarding and improving the microclimate and air quality; Preserving and enhancing soil functions and the water balance; Creating and enhancing the quality of habitats for plant and animals; Improving the residential environment	None
	Green building	DGNB Certification System 2018	Environmental Quality (22.6%) Economic Quality (22.5%) Sociocultural and Functional Quality (22.4%) Technical Quality (15.2%) Process Quality (12.3%) Site Quality (5%)	Platinum; Gold; Silver; Bronze

Table A3. *Cont.*

Country	Type	System	Content	Rating
the United States of America	Green roof	Green Factor	Improves the look and feel of a neighborhood; Reduces stormwater runoff; Cools cities during heat waves; Provides habitat for birds and beneficial insects; Supports adjacent businesses; Decreases crime	None
	Green building	LEED	Integrative Process (1%) Location and Transportation (25%) Sustainable Sites (8%) Water Efficiency (9%) Energy and Atmosphere (26%) Materials and Resources (10%) Indoor Environmental Quality (13%) Innovation (5%) Regional Priority (3%)	Platinum; Gold; Silver; Certified
Brazil	Green roof	None	None	None
	Green building	LEED; Alta Qualidade Ambiental–Haute Qualité Environnementale	LEED: Same as LEED in the United States of America Alta Qualidade Ambiental–Haute Qualité Environnementale: Considers culture, climate, technical standards, and regulations existent in Brazil. The system contains 14 categories for rating quality of the built environment.	LEED: Platinum; Gold; Silver; Certified Alta Qualidade Ambiental–Haute Qualité Environnementale: Basic; Good, Best
Australia	Green roof	Green Factor	Urban heat island effect reduction; Biodiversity and habitat provision; Stormwater reduction; Social amenity such as recreation and mental well-being; Urban food production; Aesthetic values	None
	Green building	Green Star (Design and As Built Version 1.3)	Management (13%) Indoor Environment Quality (15%) Energy (20%) Transport (9%) Water (11%) Materials (13%) Land use and ecology (5%) Emissions (5%) Innovation (9%)	6 star; 5 star; 4 star

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