applied sciences

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Inventory of Urban Building Roof Space and Analysis of Agricultural Production Potential—A Case Study

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Abstract: Utilizing idle space for agricultural planting can generate production profits while greening the urban environment. How can the space available for agricultural planting in cities be inventoried and quantified, and what is the production potential? With the help of GIS, spatial analysis was carried out, and more objective conclusions were drawn through calculation. This paper takes the roof space in Shibei District of Qingdao as an example to study: First, we analyzed the influencing factors and inventory standards of roof agricultural planting; second, we selected inventory standards for idle roof space inventory and conducted statistical analysis of the data obtained from the inventory. Furthermore, combining the annual yield of vegetables per unit area and the annual consumption standards of vegetables by citizens, we calculated the yield and supply and demand; next, we summarized the research results, analyzed their reliability and the advantages and disadvantages of this inventory, and derived formulas for calculating the agricultural production potential of rooftops and urban spaces. Finally, we concluded that the idle roof area in cities and the potential for agricultural production are significant. The research results indicate that the roof area of urban buildings in the Shibei District of Qingdao is 383.3 hectares, with an annual vegetable production potential of 25,800 tons, which can supply the urban population of 184,300. Based on the above research, it is proposed that rooftop agriculture should be given priority in the future development of urban agriculture, and it is recommended that other urban spaces should be inventoried to promote the development of urban agriculture.

Keywords: rooftop agriculture; space inventory; analysis of agricultural production potential; urban agriculture

Citation: Wang, X.; Zhang, X. Inventory of Urban Building Roof Space and Analysis of Agricultural Production Potential—A Case Study. *Appl. Sci.* **2023**, *13*, 10300. https://doi.org/10.3390/app131810300

Academic Editor: Nathan J. Moore

Received: 14 August 2023
Revised: 8 September 2023
Accepted: 10 September 2023
Published: 14 September 2023

1. Introduction

Cultivated land resources are very valuable, and in the current situation of scarce cultivated land resources, urban agriculture is a good solution. Urban agriculture is an agricultural production activity carried out in urban built-up areas. By tapping into the existing green production potential of cities and improving their ecological carrying capacity, it can increase the effective supply of arable land, reduce resource consumption, improve the ecological environment, bring material output, and promote interpersonal communication. It has important ecological, economic, and social significance. Since 2005, many cities and regions in Western countries have conducted land inventories using geographic information systems and aerial images to determine the land available for agricultural development in cities [1–6] and to evaluate the production potential of urban agricultural land [5–9].

Currently, the development models of urban agriculture mainly include rooftop agriculture, community agriculture, vertical farms, etc. Among them, rooftop agriculture refers to the use of idle space on the roof to develop agriculture. This model not only helps to alleviate the urban heat-island effect but also can produce more green vegetables without occupying new urban construction land. The use of idle roofs for agricultural planting is also of great benefit to the landscape, bringing ecological benefits [10]. Many scholars have conducted a series of investigations and studies on the available space of building roofs in cities, focusing on inventory methods, inventory standards, and other aspects. The current practices and standards for roof space inventory are mainly as follows: Berg et al. reviewed the suitability of vacant rooftop spaces in New York City, used public data to determine suitable buildings for different farming methods (including considering structural factors), and combined these data with aerial imagery to verify and estimate the available area. Boston conducted an inventory of roofs with a minimum roof area of 93 m^2 (1000 ft^2), a maximum building height of 30.48 m (100 ft), and a surface slope of <5° [7]. In the inventory of rooftop agricultural production space conducted by Columbia University in New York City, the following standards were adopted: The building was located in a commercial and industrial area; the requirement for the roof to withstand a live load during construction within a certain time range was 2.4 KN/m^2 (50 pounds per square foot); it covered an area of over 929 m^2, avoiding small-scale roof planting with greater economic uncertainty; the building height was about ten stories; and the buildings could not be used for heavy industry or hazardous substance production [11]. Dang et al. used LASools to generate digital terrain models and digital surface models and then used GIS to calculate roof slopes to detect roofs with slopes below 5 degrees within 69% of the total area of Rio de Janeiro and evaluate their vegetable production needs. The research results indicated that 1385 hectares of roofs within the scope of this study are suitable for agricultural cultivation, and the vegetables produced can meet 39.2% of the annual vegetable needs of residents in Rio de Janeiro [12]. Haberman et al. used ArcMap 10.1 and Google Earth 6.2 to analyze the industrial rooftop space in Montreal and used hydroponic methods to grow vegetables. The results showed that its yield could easily meet the city's vegetable needs [13]. Nadal et al. used light detection and ranging (LIDAR) and long-wave infrared (LWIR) data, Leica ALS50-II, and TASI-600 sensors to identify some building roof parameters (area, slope, material, and solar radiation) to determine the potential for building roof agriculture and applied this method to non-residential urban areas of the Rubi Industrial Estate in Barcelona, Spain. The study found that 36,312 m^2 of the 1,243,540 m^2 of roofs have ideal characteristics for roof agriculture construction, which can produce about 600 tons of tomatoes annually, accounting for 50% of the total population of Rubi [8]. In the roof inventory of a certain block in Tianjin, Zhao Man considered 12 evaluation indicators, such as sunlight obstruction, roof materials, roof bearing capacity, slope, building location, building function, and height. Through inventory screening and spatial information data overlay analysis, Zhao finally obtained a roof suitability score and ranking that can be used for agricultural planting [14]. This method is more suitable for small-scale roof inventory or secondary inventory of agricultural potential on selected roofs. In summary, the current roof inventory standards mainly include roof area size, slope, height, building function, load capacity, lighting, and other aspects. The inventory standards in different regions are related to local building regulations, building characteristics, and residents' lifestyles. Therefore, it is necessary to conduct in-depth research on urban building roof inventory in different regions.

The inventory of urban agricultural land in China started relatively late, and there is currently a lack of research on methods for the inventory and potential assessment of roofs and more types of spaces at the urban, county, and district levels. However, rooftop agriculture has obvious advantages in various development models of urban agriculture and has developed rapidly. Therefore, it is necessary to continue conducting building rooftop agriculture inventory and agricultural production potential research at the county and district levels. This article takes the rooftop space in the Shibei District of Qingdao as an example for conducting inventory and analysis of agricultural production potential. Here, agricultural production refers only to agricultural cultivation, and the planting varieties are mainly vegetables. Firstly, we established and selected inventory standards. Based on this, we collected rooftop spatial information data using satellite remote sensing maps, urban related data, on-site research, and other methods. With the help of the ArcGIS platform and combined with a comprehensive interpretation method, we constructed a spatial information database. Next, taking into account various inventory standards, we used GIS for overlay analysis, assisted by tools such as Excel (https://www.microsoft.com/zh-cn/microsoft-365/excel, accessed on 13 August 2023) and Photoshop (http://www.adobe.com/, accessed on 13 August 2023), to collect data and draw a spatial distribution map of agricultural potential. Subsequently, combined with design and technical strategies, based on different spatial attribute characteristics, agricultural production mode selection and potential evaluation calculations were carried out. The calculation was based on the annual crop yield per unit area and per capita annual consumption standards under different production methods, and objective data were used to achieve empirical analysis of the production potential of rooftop agriculture. Based on the above research, formulas for calculating the agricultural production potential of rooftops and urban spaces were derived, and we summarized the process and methods of roof space inventory and potential assessment and drew a framework diagram. The above research fills the gap in large-scale roof space inventory in China, improves the theoretical research related to urban space inventory, and provides a practical and convenient calculation basis and method reference for inventory and potential assessment work.

2. Introduction to the Research Area

2.1. Natural Geographical Conditions

This study takes the Shibei District of Qingdao as an example. The basic conditions for developing urban agriculture in this area are as follows: Qingdao City is located in the southeast of Shandong Peninsula, including seven districts, such as Shinan, Shibei, and Licang, and three cities, such as Pingdu, Jiaozhou, and Laixi. The first three districts are the central jurisdiction of Qingdao, while Shibei District is basically located in the center of the jurisdiction, far from suburban agriculture, making the development of urban agriculture significant. Shibei District covers an area of 66 square kilometers, including the old urban area and some new areas. There are relatively few vacant plots, and it is advisable to develop urban agriculture through rooftop agriculture. By the end of 2022, statistical data showed that the permanent resident population of Qingdao was 10.3421 million. Among them, the permanent population of the districts and urban areas was 7.41 million, the population of the three districts in the city was 2.55 million, and the population of Shibei District was the largest, which was 1.09 million. The overall urbanization rate of Qingdao has reached 77.32%, higher than the national average level.

Qingdao is located in hilly terrain, and the urban terrain has a certain undulating quality. The Shibei District is mainly characterized by hilly terrain, with high terrain in the east and low terrain in the west. The urban area of Qingdao is directly regulated by the marine environment, with significant marine climate characteristics, such as humid air and abundant rainfall. The annual average temperature is 12.7 °C, with moderate temperature and four distinct seasons. Qingdao has abundant wind energy resources and good solar energy resources, with a total annual solar radiation of 120 kcal/cm^2.

From the above, it can be seen that the climate in Shibei District of Qingdao is suitable, with abundant rainfall, for agricultural cultivation, and the urban agricultural development conditions are good. Light and wind energy resources are abundant and can provide energy supply for agricultural cultivation.

2.2. Research Data Sources

The main work of this study was as follows: (1) We conducted an inventory, determined statistics, and analyzed the idle roof area in the Shibei District of Qingdao; (2) we selected planting methods and calculated the production potential for the identified roofs. The work (1) was carried out using GIS analysis software (https://developers.arcgis.com/javascript/latest/, accessed on 13 August 2023) combined with Google Satellite Maps as well as high-definition satellite images, Baidu panoramic images, on-site inspections, and other methods. Considering the computer data processing capability and considering the clarity of the analysis image as much as possible, we selecte3d Google Satellite Maps with a pixel resolution of 0.96 m for this purpose. These image and the high-definition satellite map (with a resolution of 0.24 m) were obtained through BIGMAP software (http://www.bigemap.com/, accessed on 13 August 2023). Baidu Panorama was obtained and observed online in real time. For some unclear current spaces, on-site inspections were conducted. The required vegetable yield and other data for job (2) were obtained through relevant statistical data in recent years and weighted calculations of data under different planting conditions.

3. Determine Inventory Standards

3.1. Influencing Factors and Inventory Standards of Rooftop Farming

The use of roofs for agricultural planting activities is influenced by multiple factors, such as roof slope, height, area, bearing capacity, lighting conditions, building type, roof surrounding environment, urban regulations, etc. The more comprehensive the various factors considered, the higher the feasibility of rooftop agricultural planting activities. The influencing factors, inventory basis, and inventory standards of rooftop agricultural planting were analyzed, as shown in Table 1. In addition, the regularity, accessibility, ownership, local climate, management issues, and building location of the roof space can all affect the development of agricultural planting activities and can be analyzed and considered based on specific circumstances without going into detail here.

Table 1. The influencing factors and inventory standards of rooftop agricultural planting.

Influencing Factors	Impact on Agricultural Planting Activities	Inventory Basis	Inventory Standards
Roof slope	A certain slope is beneficial for drainage, but too large a slope is not suitable for people and planting activities.	Flat roofs and pitched roofs with a slope of less than 15° (i.e., 26%) are suitable for roof greening [15]; "The Unified Standard for Civil Building Design" mentions that the slope of a flat roof is ≥2% and <5%, and the slope of a planted roof is ≥2% and <50 [16].	On a comprehensive basis, considering the convenience of visiting people and carrying out agricultural planting activities, the flat roof within 5% should be selected.
Roof height	As the height of the building increases and the wind force increases, it will affect the planting.	Beijing requires that non-sloping rooftop public buildings with fewer than 12 floors and a height of less than 40 m should implement roof greening, with a greening area of over 30% [17]; cities such as Meishan and Chengdu also set a ceiling height of 40 m for rooftop greening; the flat roof of public buildings with a height of no more than 50 m shall be greened according to the regulations of Shanghai City [15].	Considering the similarity between rooftop greening and agricultural planting, roof agriculture of 40 m or more is susceptible to environmental factors, and it is recommended to use 40 m as the upper limit for inventory.
Roof area and availability	A roof with a large area and good usability (regular shape and flat surface) facilitates the installation of greenhouses and the formation of certain scale benefits.	Li Bojun mentioned that rooftop vegetable fields of 10–15 m^2 can meet the per capita annual vegetable consumption. Greenhouses require a certain degree of scale efficiency, and small greenhouses should be around 400 square meters. According to an area utilization rate of 84.7% [18], the roof area should be over 500 square meters; the scale of greenhouse construction in China, in order of small, medium, and large, is 5000 square meters, 5000 to 20,000 square meters, and over 20,000 square meters, which is relatively large for cities; the area of urban greenhouses with different functions may vary. However, due to the lack of large rooftops in urban buildings, the scale of greenhouses can be appropriately reduced.	It is advisable to select 15 square meters as the minimum roof inventory standard and use 500 square meters and 5000 square meters as the area boundary to facilitate the selection of different agricultural planting methods according to different situations.

Table 1. *Cont.*

Influencing Factors	Impact on Agricultural Planting Activities	Inventory Basis	Inventory Standards
Building type/function	The different types and functions of buildings as well as the different characteristics of roofs affect the selection of agricultural planting methods and the development of activities.	The roof of residential buildings has good lighting and a demand for vegetables and fruits. The roof area is small and suitable for soil cultivation and outdoor facility cultivation; the roof area of public and industrial buildings is large, with strong commonality, making it suitable for commercial rooftop greenhouses; roof agriculture should not be carried out in buildings with pollution; buildings with parking functions on the roof are not considered; roof agriculture will not be considered for historic and protected buildings, those whose planting has a negative impact on the functionality of the building, and those whose roofs require significant renovation before planting activities can be carried out.	Distinguish the types of buildings into residential, public, industrial, etc.; exclude polluting buildings, special buildings, and buildings with functional roof requirements.
Roof load capacity	The roof must meet the load requirements generated by planting soil, planting facilities, and human activities.	The roof greening code mentions that the roof load of the greening roof should be $\geq$3 KN/m^2. The Shanghai roof greening standard points out that the roof load of the combined greening roof should be $\geq$4.5 KN/m^2 (covered with 30 cm soil), and the roof load of the lawn greening roof should be $\geq$2.5 KN/m^2 (covered with 10 cm soil) [15]. The planting depth and load of soil-cultivated agriculture are basically between the above two; roof hydroponic greenhouses, generally, for accessible roofs are not restricted, and for some restricted roofs, structural reinforcement can be used to achieve this.	Based on comprehensive analysis, the roof soil cultivation agriculture planting should have a roof load capacity of $\geq$3 KN/m^2; container cultivation, soilless cultivation, etc., are basically unrestricted.
Roof lighting conditions	Vegetable growth requires a certain amount of lighting time and the lighting; conditions on the roof affect the planting effect.	Different types of vegetables have different requirements for sunlight duration and light intensity. The sunlight duration is divided into long, short, and medium, while the light intensity is divided into strong, weak, and medium; the sunshine demand for vegetables ranges from 12 to 14 h, below 12 h, etc., and generally should be more than 8 h; greenhouse planting should rely on natural light. If it is not possible to obtain it, supplementary light sources can be used.	Conduct sunshine analysis to determine if the roof meets the sunshine duration of 8 h; for those who are not satisfied, consider adopting greenhouse planting with environmental regulation.
Surrounding environment	Roof greenhouses, planting facilities, etc., can cause obstruction and impact on surrounding buildings and the environment.	Greenhouses should not be built on residential roofs, as they are small and uneconomical in scale and can easily block the surrounding residential areas from sunlight; when the greenhouse is built on the roof of a public building, the minimum sunlight standard requirements of the building on the north side should be ensured; the installation of rooftop greenhouses and planting facilities (such as sheds) should be considered, combined with the surrounding environmental requirements and paying attention to volume and aesthetics; roof agriculture should not be carried out in areas with high environmental landscape requirements, such as historical building protection areas, coastal areas, tourist landscape areas, etc.	Analyze whether the greenhouse has caused obstruction, and if there is no sunlight requirement, it is not limited. If there is obstruction, it can be treated through partial coverage, retreat, etc.; areas with high landscape requirements do not consider rooftop agriculture.

3.2. Roof Space Inventory Standards in Shibei District

Based on the above analysis, roof agriculture planting is influenced by many factors, and the analysis work is relatively complex. When conducting inventory activities, the inventory standards should be determined based on the purpose of the inventory and the manpower and time invested. The purpose of this inventory is as follows: from the perspective of urban spatial utilization, taking into account the main influencing factors of rooftop agricultural planting, analyzing idle roofs, obtaining roof distribution maps and area data that can be used for developing agricultural planting, and then calculating the production potential of rooftop agriculture, inferring its development feasibility. Based on the limited inventory personnel and available time, taking into account good feasibility and accuracy, we decided to consider the first four significant influencing factors in Table 1 (roof slope, height, area and availability, and building type) for inventory. The building type was divided into residential and other two categories.

4. Inventory and Analysis

4.1. Inventory of Roof Space in the Shibei District

4.1.1. Inventory Methods

Firstly, we selected Google Satellite Maps with a pixel resolution of 0.96 m for analysis. Next, we imported satellite images into GIS, visually interpreted and analyzed the properties of building roofs in the images, and determined their area by drawing and quantifying the surface of the building roof. Some roof outlines were not clear enough and were compared with Google's satellite map with a pixel resolution of 0.24 m and the Panorama in Baidu Maps, and some ambiguous spaces were investigated on the spot. According to the aforementioned inventory standards, using satellite remote sensing images, the roofs of buildings with sloping roofs and heights exceeding 40 m as well as the roofs of buildings with pollution and those unsuitable for agricultural cultivation in the rubber industry and industrial production and those used for parking lots were removed and not considered, neglecting those whose available space on the roof was too fragmented or too small in area. We only inspected flat roofs that were conducive to agricultural development and assigned residential and other attributes to the inspected buildings. During the inventory process, in order to avoid individual roof omissions and confusion in the inventory, it was carried out block by block, and the data were promptly checked and saved at any time.

4.1.2. Inventory Results

The distribution map of available roofs in the Shibei District of Qingdao was drawn through inventory, as shown in Figure 1. It can be seen from the distribution map that the available roofs are mainly concentrated in the middle and south of Shibei District and less so in the northwest and eastern areas. The reasons are as follows: The harbor wharf and some extension areas along the blue sea area in the west of the Shibei District are mainly industrial and high-rise buildings. The east side is the Fushanhou New Area after the expansion of the urban area in recent years. The buildings are mainly pitched roofs and high-rise buildings as well as some other types of flat-roof buildings. According to different types of buildings, they were divided into two categories: residential and other buildings. The statistical results are shown in Table 2. Finally, it was concluded that there are a total of 5997 effective roofs, covering an area of 383.3 hectares.

The roof surface of a building cannot be completely covered for vegetable and fruits planting, and it also requires corresponding planting management and activity areas. The proportion of the available roof area to the roof area, i.e., the utilization rate of the roof area, is influenced by multiple factors: (1) The first is the planting method and layout method. The utilization rate of roof area varies from large to small in three ways: soil cultivation with full coverage, strip layout planting, and point planting ponds or container planting. (2) The second factor is the impact of roof area size and regularity. A roof with a large area, flat surface, and regular shape can be considered for arranging a multi-span greenhouse, which has the highest area utilization rate. The area utilization rate of a regular square roof is higher than that of an irregular polygon. The layout of local stairwells, shapes, and cooling towers on the roof can affect the area utilization rate. Here, the average utilization rate of roof area obtained from Li Bojun's research is 84.7% [18]. According to this ratio, the available roof area of Shibei District is 324.6 hectares.

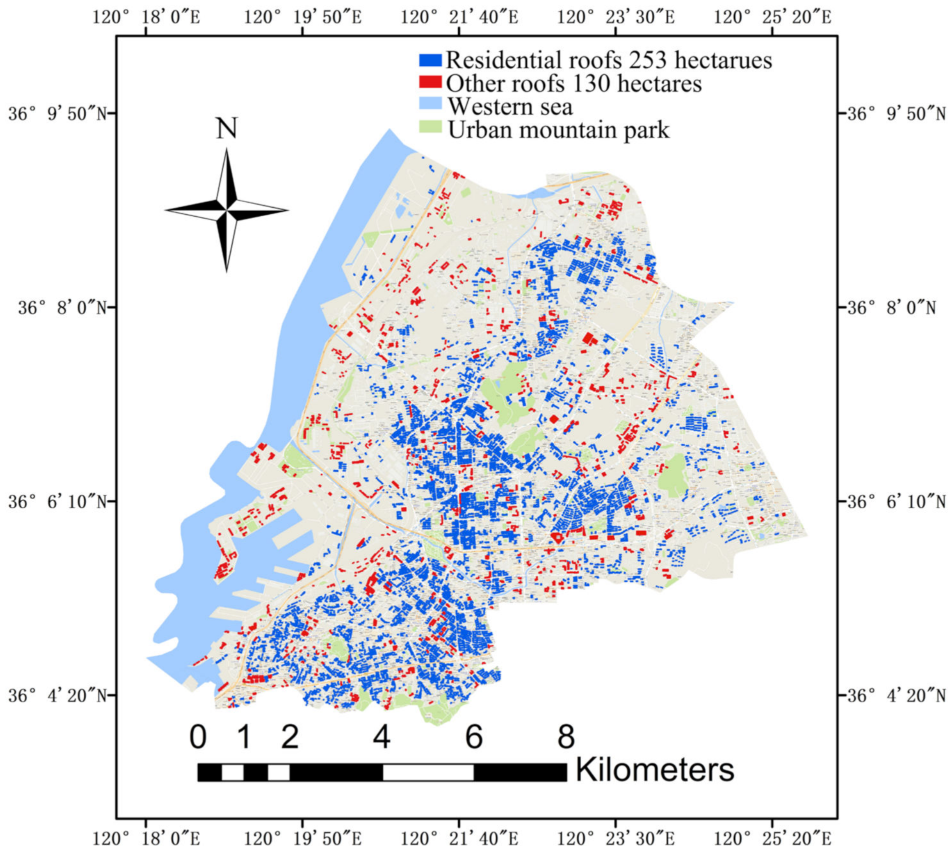


Figure 1. Distribution map of available roofs in the Shibei District of Qingdao by building type; Source: self-drawn.

Table 2. Inventory results of available roofs in Shibei District of Qingdao (classification by building type).

Type Indicator	Quantity (Piece)	Area (Hectare) (Available Area Converted at 84.7%)
Residential building roofs	4859	253.3 hectares (available area 214.5 hectares)
Other building roofs	1138	130.0 hectares (usable area 110.1 hectares)
Total	5997	383.3 hectares (available area 324.6 hectares)

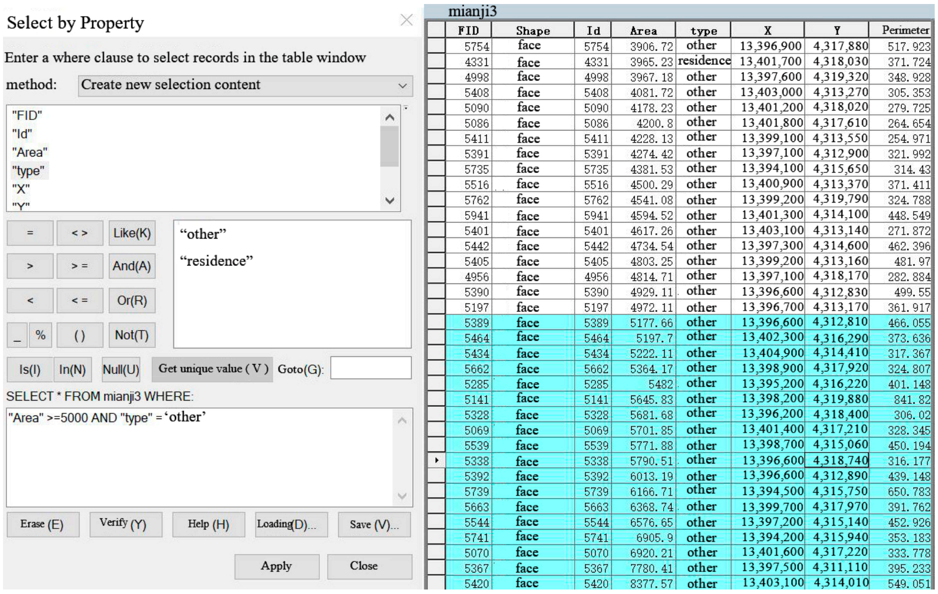
4.1.3. Suitability of Inventory Results

We next reanalyzed the roof distribution map and related data obtained from the first inventory.

The suitability of using roofs for agricultural planting activities is called rooftop agricultural suitability. Considering the roof area and building type comprehensively, the suitability of roof agriculture was divided into three levels: Level 1 is the most suitable for developing roof agriculture, with the best economy. Level 2 is more suitable for developing rooftop agriculture and has better economic efficiency. Level 3 is suitable for developing rooftop agriculture, with average economic efficiency.

Analysis and statistics of the inventory data indicated that the roof area ranges from a few square meters to 26,000 square meters. According to the three ranges of 15–500 square meters, 500–5000 square meters, and over 5000 square meters and combined with the influencing factors of building type/function and roof area in Table 1, the suitability level of roofs was assigned according to the following combinations: (1) Other types of buildings, including public buildings, industrial buildings, etc., have larger roof areas, which are more suitable for developing rooftop greenhouses and have better economic efficiency. The roof scale was divided into three levels from large to small, and those that met the requirements of "area" ≥5000 and "type" = "other" were selected and assigned as level 1 (Figure 2). We assigned the "other" building roofs between 500 (excluding) and 5000 (excluding) to level 2, and we assigned the "other" building roofs between 15 (inclusive) and 500 (inclusive) square meters to level 3. (2) The roof area of the residential buildings is not more than 5000 square meters, so it was divided into two and three levels according to 500 (excluding)–5000 (excluding) square meters and 15 (including)–500 (including) square meters.

By assigning colors according to different suitability levels, the available roof distribution map displayed by suitability level was obtained, as shown in Figure 3. Statistical analysis was conducted on the relevant data, including building type, roof area, and suitability level, resulting in Table 3.



FID	Shape	Id	Area	type	X	Y	Perimeter
5754	face	5754	3906.72	other	13,396,900	4,317,880	517.923
4331	face	4331	3965.23	residence	13,401,700	4,318,030	371.724
4998	face	4998	3967.18	other	13,397,600	4,319,320	348.928
5408	face	5408	4081.72	other	13,403,000	4,313,270	305.353
5090	face	5090	4178.23	other	13,401,200	4,318,020	279.725
5086	face	5086	4200.8	other	13,401,800	4,317,610	264.654
5411	face	5411	4228.13	other	13,399,100	4,313,550	254.971
5391	face	5391	4274.42	other	13,397,100	4,312,900	321.992
5735	face	5735	4381.53	other	13,394,100	4,315,650	314.43
5516	face	5516	4500.29	other	13,400,900	4,313,370	371.411
5762	face	5762	4541.08	other	13,399,200	4,319,790	324.788
5941	face	5941	4594.52	other	13,401,300	4,314,100	448.549
5401	face	5401	4617.26	other	13,403,100	4,313,140	271.872
5442	face	5442	4734.54	other	13,397,300	4,314,600	462.396
5405	face	5405	4803.25	other	13,399,200	4,313,160	481.97
4956	face	4956	4814.71	other	13,397,100	4,318,170	282.884
5390	face	5390	4929.11	other	13,396,600	4,312,830	499.55
5197	face	5197	4972.11	other	13,396,700	4,313,170	361.917
5389	face	5389	5177.66	other	13,396,600	4,312,810	466.055
5464	face	5464	5197.7	other	13,402,300	4,316,290	373.636
5434	face	5434	5222.11	other	13,404,900	4,314,410	317.367
5662	face	5662	5364.17	other	13,398,900	4,317,920	324.807
5285	face	5285	5482	other	13,395,200	4,316,220	401.148
5141	face	5141	5645.83	other	13,398,200	4,319,880	841.82
5328	face	5328	5681.68	other	13,396,200	4,318,400	306.02
5069	face	5069	5701.85	other	13,401,400	4,317,210	328.345
5539	face	5539	5771.88	other	13,398,700	4,315,060	450.194
5338	face	5338	5790.51	other	13,396,600	4,318,740	316.177
5392	face	5392	6013.19	other	13,396,600	4,312,890	439.148
5739	face	5739	6166.71	other	13,394,500	4,315,750	650.783
5663	face	5663	6368.74	other	13,399,700	4,317,970	391.762
5544	face	5544	6576.65	other	13,397,200	4,315,140	452.926
5741	face	5741	6905.9	other	13,394,200	4,315,940	353.183
5070	face	5070	6920.21	other	13,401,600	4,317,220	333.778
5367	face	5367	7780.41	other	13,397,500	4,311,110	395.233
5420	face	5420	8377.57	other	13,403,100	4,314,010	549.051

Figure 2. Screenshot of roof suitability level analysis process. Blue represents data for roofs with an area greater than 5000; Source: self-analysis.

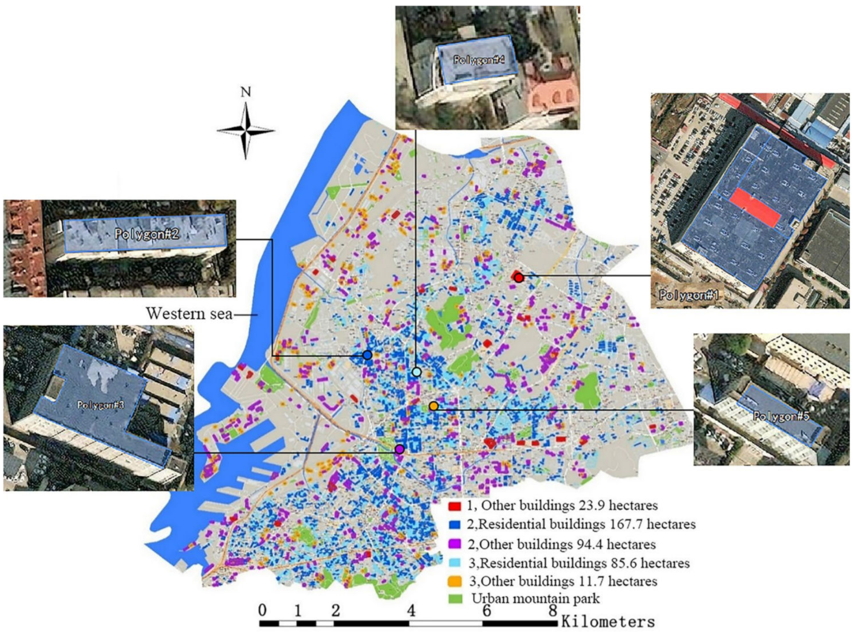


Figure 3. Distribution map of available roofs in the Shibei District of Qingdao by suitability level; Source: self-drawn.

Table 3. Inventory results of available roofs in the Shibei District of Qingdao (classification by suitability level).

Building Type	Roof Area S (ha)		Suitability Level	Proportion of Area	Quantity (Pieces)		Area (ha)
Residential buildings	$15 \leq S \leq 500$	85.60	Level 3	22.33%	2781	4859	253.3
	$500 < S < 5000$	167.7	Level 2	43.76%	2078		
Other types of buildings	$15 \leq S \leq 500$	11.7	Level 3	3.05%	403	1138	130.0
	$500 < S < 5000$	94.4	Level 2	24.63%	708		
	$5000 \leq S$	23.9	Level 1	6.24%	27		
		Total				5997	383.3

4.2. Analysis of Rooftop Agricultural Production Potential in Shibei District

Based on the completion of the above inventory, we calculated the annual production potential of rooftop agriculture and analyzed the supply and demand of urban vegetables. Considering the two influencing factors of roof area and building type comprehensively, we selected different vegetable cultivation methods, and combined with the annual output per unit area of vegetables under the corresponding cultivation methods, the annual production of rooftop vegetables was calculated, and then, the urban vegetable supply and demand analysis was carried out in combination with the annual vegetable consumption standard and the number of people in the Shibei District of Qingdao. Firstly, we calculated the annual yield per unit area under different vegetable cultivation methods.

4.2.1. Determine the Annual Yield per Unit Area of Vegetables under Different Cultivation Methods

According to national statistical data, the unit area yield of vegetables in China in 2016 was 3.57 kg/m^2 [19]. The total vegetable production was 798 million tons, of which the facility vegetable production (excluding fruits and melons) was 252 million tons, with a unit area yield of 6.44 kg/m^2. The yield of soil-cultivated vegetables was 546 million tons, with a unit area yield of 2.97 kg/m^2. In addition, differences in planting varieties, regions, and facilities also result in significant differences in annual yield per square meter. For example, the average annual yield of greenhouse tomatoes in China can reach 10–15 kg/m^2, and cucumbers can reach 15–20 kg/m^2, which is significantly higher than other vegetables. Foreign glass greenhouse tomatoes have a yield of up to 40–80 kg per square meter, and they are at a leading level in variety selection, cultivation techniques, environmental regulation, and other aspects. China's facility horticulture is still mainly produced and operated by individual farmers, with a relatively low level of industrialization. Another study pointed out that China has the world's largest facility agriculture area, with over 90% of it engaged in vegetable production, but the average annual yield of greenhouse vegetables is only about 9 kg/m^2. From the above various data, it can be seen that the yield of facility cultivation is significantly better than that of soil cultivation, but there is no quantitative standard for vegetable yield per unit area under different greenhouse types, planting varieties, and technical conditions. The introduction of facility agriculture in urban areas in the future will help increase urban vegetable production and enrich urban vegetable varieties. Table 4 shows the relevant data of some examples of facility cultivation and soil cultivation. By analyzing and weighting these data, the reference standards for annual yield per unit area of soil cultivation and facility cultivation were obtained in order to improve the reliability and accuracy of the reference data as much as possible and reduce the calculation error of total vegetable yield.

The numerical values of vegetable yield from national and some practical cases are cited here without citing the local vegetable yield data in Qingdao. This is because the vegetable yield per unit area is not only affected by the planting area but also by various factors such as planting varieties and facilities. In addition, there are no reliable data on roof agriculture planting in Qingdao, so it is not possible to comprehensively consider various factors. In this case, using the current actual vegetable production in China as the main reference enabled the obtained data to be applied in the calculation of potential in more regions. However, it should be noted that in order to reduce errors in the calculation of agricultural production potential in a certain region, production data from the same climate zone, planting facilities, and varieties should be referred to as much as possible.

Table 4. Examples of facility cultivation and soil cultivation and analysis of annual yield per unit area of vegetables.

Examples of Facility Cultivation	Area (m^2)	Vegetable Variety and Yield	Annual Output per Unit Area (kg/m^2)	Remarks
The Green Dot Roof Greenhouse in Brooklyn, New York [20]	1400 m^2	Green leafy vegetables, with an annual output of 45,000 kg	32.1 kg/m^2	Adopting a glass greenhouse with a higher yield
Shanghai Ground Greenhouse Crops [21]	12,500 m^2 7500 m^2 5000 m^2 5000 m^2	Tomatoes 32.10 kg/m^2, cherry tomato 17.92 kg/m^2, cucumber 30.02 kg/m^2, and sweet pepper 15.33 kg/m^2	Average 23.8 kg/m^2	Mostly high-yielding vegetables
Facility cultivation vegetables in China [19]	58.721 million mu	252 million tons	6.44 kg/m^2	Average production capacity under existing facility cultivation techniques;
Annual yield per unit area of facility cultivation			15.04 kg/m^2	see supplementary data for details (1)
Examples of soil cultivation	Area (m^2)	Vegetable variety and yield	Annual output per unit area kg/m^2	notes
Rooftop soil farms in Brooklyn, New York [20]	10,000 m^2	Vegetables, chickens, bees; annual production of 50,000 pounds, 22,680 kg	2.3 kg/m^2	
Li Bojun's Roof Vegetable Cultivation Experiment [18]	Four roofs of 525.4 m^2, 593.3 m^2, 453.6 m^2, and 56 m^2	Vegetables, tomatoes, cucumbers, eggplants, radishes, loofah, etc.	12.69 kg/m^2	High level of management technology, 4-year roof cultivation experiment, and 4 farming systems
Vegetable farming in soil culture in China [19]	276.279 million mu	546 million tons	2.97 kg/m^2	
Annual yield per unit area of soil culture			4.78 kg/m^2	See supplementary data for details (2)

Supplementary data: (1) Annual yield per unit area of facility cultivation = Annual yield per unit area of facility vegetables in China (accounting for 60%) + annual yield per unit area of high-yield greenhouses on roofs and floors (accounting for 40%), that is, 6.44 × 60% + (32.1 + 23.8)/2 × 40%. (2) Annual yield per unit area of soil culture = Annual yield per unit area of soil culture vegetables in China (accounting for 60%) + average annual yield per unit area of roof soil culture at home and abroad (accounting for 40%), that is, 2.97 × 60% + (2.3 + 12.69)/2 × 40%.

4.2.2. Select the Cultivation Methods for Different Building Types of Roofs and Calculate Their Annual Yield

For residential building roofs, it is recommended to use soil cultivation as the main method, which can be combined with small arched sheds and some outdoor facilities for cultivation. The reasons are as follows: (1) There are requirements for sunlight time in residential buildings, and the height of the roof greenhouse will affect the lighting of the northern residential area, except for in new residential areas that have already considered designing a roof greenhouse in advance. (2) Proceeding from pragmatism, residents produce a large amount of organic waste in their daily life, and organic fertilizer can be obtained through composting treatment. Soil cultivation is conducive to the use of organic fertilizer for planting, thus realizing waste recycling. (3) According to relevant surveys, citizens are more inclined to simple soil cultivation with labor. (4) Soil culture more easily creates a pastoral atmosphere, with a strong sense of life and affinity for working in the field. (5) The relatively small roof area of residential buildings is not conducive to building greenhouses and maximizing their economies of scale.

For roofs of other types of buildings (public buildings, industrial buildings, etc.), it is recommended to focus on facility cultivation combined with soil cultivation. The reasons are as follows: (1) From the perspective of production efficiency, urban agricultural planting should focus on facility cultivation. The roof area of public and industrial buildings is generally large, which is conducive to the development of greenhouse agriculture. (2) Public and industrial buildings usually have their own construction scope and a certain degree of openness and openness, making them more suitable for agricultural planting activities. In the future, there should be follow-up on corresponding building regulations for rooftop agricultural facilities, and regulations and specifications should be made from the height, form, and other aspects of the facilities.

Selecting agricultural planting methods for roofs under different building types and areas in Table 3, combined with the corresponding annual yield data per unit area of facility cultivation and soil cultivation obtained in Table 4, the corresponding annual yield of roof agricultural planting was obtained after calculation, as shown in the rightmost column of Table 5. It can be seen from the data in the table that the roof agriculture planting in Shibei District can produce 25,800 tons of vegetables in total, and the annual yield per unit area is 7.95 kg/m^2, which is basically in line with the annual harvest of roof-grown vegetables of 8~21 kg/m^2, as mentioned by Li Bojun.

Table 5. Selection of roof agriculture planting mode and calculation of annual vegetable yield in the Shibei District of Qingdao.

Building Types	**Roof Area S (m^2)**	**Roof Area S (ha)**	**Suitability**	**Usable Area(ha)**	**Suggested Planting Method**	**Annual Production (kg)**
Other types of buildings	$5000 \leq S$	23.9	Level 1	20.2	Facility cultivation	0.30×10^7
	$500 < S < 5000$	94.4	Level 2	80.0	Facility cultivation	1.20×10^7
	$15 \leq S \leq 500$	11.7	Level 3	9.9	Soil cultivation	0.05×10^7
Residential buildings	$500 < S < 5000$	167.7	Level 2	142.0	Soil cultivation	0.68×10^7
	$15 \leq S \leq 500$	85.6	Level 3	72.5	Soil cultivation	0.35×10^7
Total		383.3		324.6		2.58×10^7
Annual yield per unit area				7.95 kg/m^2		

4.2.3. Determine the Number of Rooftop Vegetables Supplied to the Population Based on the per Capita Annual Consumption of Vegetables

The annual per capita vegetable consumption in China's Food and Nutrition Development Outline (2014–2020) is 140 kg. Based on this standard, combined with the annual vegetable production of 25,800 tons of rooftop agriculture planting in the Shibei District of Qingdao, it can be calculated that this production can supply the urban population of 184,300, accounting for 16.9% of the total population of 1.09 million in the Shibei District of Qingdao.

4.3. Framework for Inventory and Potential Assessment Methods

We sorted out the process of roof space inventory and agricultural production potential assessment in the previous text, summarized the entire process, and established the following concise method framework diagram (Figure 4).

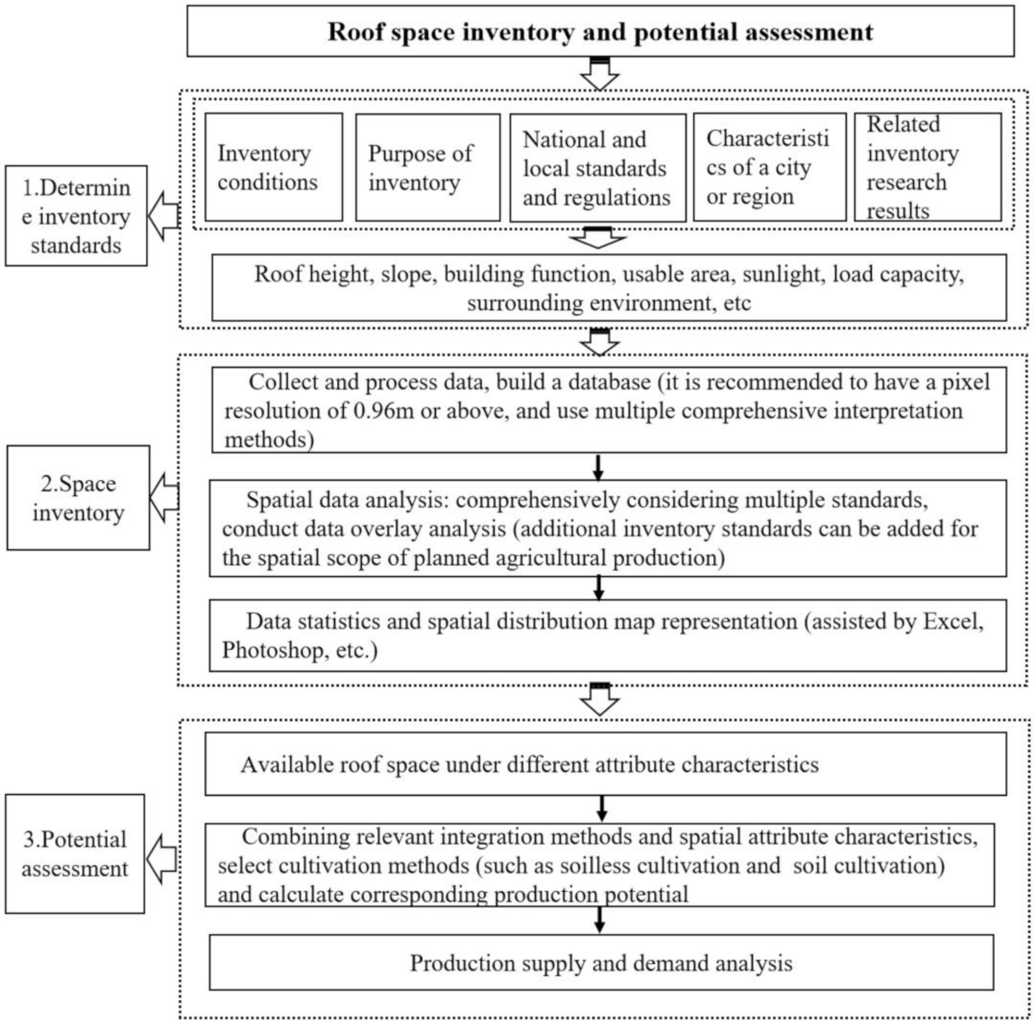


Figure 4. Framework for roof space inventory and potential assessment process methodology; Source: self-drawn.

5. Discussion on Relevant Issues

5.1. Reliability of Research Results and Data Anlysis

This project carefully considered and controlled every step of the process from roof space inventory to agricultural production potential calculation: (1) Considering four obvious factors that affect roof agricultural planting (roof height, slope, area, and building type), a roof space inventory was conducted. (2) By importing Google Satellite Maps into GIS for roof space analysis, various methods such as high-definition satellite maps, Baidu panoramic maps, and on-site inspections were combined to improve the accuracy of the analysis. (3) Referring to multiple data sources, we obtained the annual yield of vegetables per unit area under different cultivation methods through weighted calculation. (4) Based on the inventory data and considering the utilization rate of roof area, the selection of different cultivation methods and production potential calculation for roof agriculture was carried out based on the type of building and roof area. From the above analysis, it can be seen that each step of the research aimed to comprehensively consider the problem, and the data collection and application were rigorous to minimize errors and improve the credibility and reliability of the research results.

According to the data from this study, the usable roof area of the Qingdao Shibei District, which covers an area of 66 square kilometers, is 383.3 hectares, accounting for 5.81%. If considering the general urban spatial structure and deducting the relatively large coastal area on the west side of Shibei District (about 1258.91 hectares), the idle roof area in Shibei District accounts for 7.2 hectares per square kilometer. New York, which covers an area of 789 square kilometers, has approximately 10,000 buildings, providing 15,481.7 hectares of roof area [22], accounting for 19.6% or 19.6 hectares of roof area per square kilometer. In contrast, the 7.2% inventory result in Qingdao is relatively low. The main reasons are as follows: (1) There are many sloping roofs in the Shibei District of Qingdao, and some old buildings with flat roofs have also been affected by their top chimneys or shapes, which affects their availability. (2) This inventory removed roofs with a height of over 40 m, roofs with pollution that are not suitable for planting, small and fragmented roofs, and prefabricated iron sheet roofs. However, compared to the agricultural area inventory results of Bologna, Italy, the proportion of available roofs in Qingdao is relatively high, with only 82 hectares of roofs available in Bologna, which covers an area of 140 square kilometers [6]. This indicates that the results may also be affected by factors such as urban building density, building characteristics, and inventory methods.

During the inspection, it was also found that there was only a small amount of sporadic agricultural planting on the roofs of buildings in the Shibei District of Qingdao, and the roof agriculture was basically in a "zero state". Appolloni's study of 185 rooftop agriculture (RA) worldwide found that North America has the best development of RA, with 81 RA, 70% of which are open-air farms, of which 26 are in New York and 15 in Toronto [23]. Research has shown that these farms in North America are mainly built to improve quality of life and provide social education, with commercial operation being the second common purpose of farms [24]. Roof agriculture has developed well in developed cities mainly due to the following factors: These areas have good roof space resources, their roof agriculture developed earlier, and they have clear development goals. These country or cities have encouraged and promoted the development of roof agriculture through certain policies [25,26]. There is no policy related to rooftop agriculture in Qingdao, and overall, urban agriculture in China started relatively late [27]. The awareness of urban agriculture based on urban green living, food safety, and education is gradually emerging. However, through this inventory, the future of rooftop agriculture can be elucidated.

5.2. Advantages and Disadvantages of Inventory and Suggestions for the Development of Rooftop Agriculture

In response to this inventory, the advantages and disadvantages were analyzed and summarized as follows: Advantage 1: According to relevant urban building regulations in China, inventory standards were formulated, and the inventory methods strive to be simple and practical, which can explain problems within a certain error range and provide methods and ideas for conducting urban ground space inventory. Advantage 2: Selecting the roofs of the Shibei District of Qingdao as the GIS analysis object and utilizing the convenience of research and combined with satellite map comparison and judgment ensures the accuracy of the research results as much as possible while efficiently completing the inventory. Disadvantage 1: There were insufficient high-resolution data processing capabilities and new technology applications. A satellite image resolution of 0.96 m is average, and it is recommended to have a clearer resolution within 0.6 m. There were some rough analyses and deviations caused by subjective factors that are inevitable. There was also a failure to utilize technologies such as LIDAR and drones to improve inventory efficiency and accuracy. Disadvantage 2: The study did not comprehensively consider factors that affect agricultural planting, such as roof load capacity and lighting conditions, which also require further exploration of the practical feasibility of the identified roofs. Disadvantage 3: Qingdao is a coastal city with a large number of sloping roofs, resulting in a low amount of usable roof area, so the results are not generally universally suitable for other regions. However, from another perspective, the conservatism of the inventory data here also demonstrates the enormous potential of rooftop agriculture.

Given various constraints, this inventory work is intended to serve as a catalyst for further exploration. It is recommended to refine the relevant elements in the future roof inventory. Through the analysis of more elements, the inventory map drawn will be more detailed and feasible. Inventory work is completed through the joint efforts of governments, researchers, and various groups in the West. Its analysis of problems is more scientific and detailed, and some are worth learning from. For example, when inspecting sites, we should consider as many factors as possible that affect agricultural planting, including site characteristics, lighting conditions, surrounding environment, etc., and rank the development advantages and disadvantages [2]. In addition, inventory data can be shared on the Internet, which is beneficial for practitioners and researchers to master urban spatial information.

At present, roof agriculture in Qingdao and China has not yet achieved good development. Based on the national development environment and the results of this research, the following suggestions are given: (1) Firstly, strong policy intervention is crucial for the development and improvement of roof agriculture practices [26]. The Chinese government and cities should respond positively to urban agriculture based on goals such as food safety, improving urban quality of life, and education and make corresponding policies and incentives, such as legalizing and standardizing urban agricultural behavior, providing certain financial support, technical assistance, and encouragement. (2) Regarding overcoming obstacles to development, the development of rooftop agriculture is relatively slow in China. In addition to the unavailability or inconvenience of spatial use, there are also problems with traditional thinking such as "agriculture in the suburbs", insufficient bearing capacity of old building structures, poor accessibility, the high time and financial cost of construction and maintenance, and intermittent planting during cold and hot seasons [28]. These problems need to be gradually overcome, including promoting awareness of rooftop agriculture through publicity and education, guiding and driving the development of rooftop agriculture through the construction of demonstration projects, incorporating rooftop agriculture into the design plan when building new buildings to meet bearing capacity, the structural renovation of old buildings, improving roof accessibility, and financial subsidies. (3) Different planting methods should be adopted for different types of building roofs. Chinese residential buildings mainly consist of multiple floors and high-rise buildings. In terms of planting methods, it is recommended to adopt open-air soil cultivation based on reasons such as organic waste reuse, economic cost, labor exchange, and not blocking sunlight, and the roof space should be divided on a household basis. There are fewer private single-family homes or townhouses, usually with courtyards, which can be directly utilized. It is recommended to use commercial rooftop greenhouses on the roofs of public or industrial buildings to improve planting efficiency. (4) Good production should be established through usage channels to promote the development of urban agriculture. For example, residential vegetables are mainly grown for self-consumption and sold in excess, and vegetables produced in other buildings can be supplied to hotels, schools, etc., or connections can be established with communities and residents for sale. (5) The appropriate variety of rooftop vegetables should be considered. Roof agriculture currently mainly includes two types: open-air soil cultivation farms or gardens and roof greenhouses. The former planting medium includes soil and light planting mixture, etc. When selecting vegetable planting varieties, roof agriculture using soil planting can choose various vegetables such as green peppers, tomatoes, cucumbers, scallions, etc. When using light planting mixture and shallow medium without soil, lettuce, kale, and other salad vegetables are more suitable. Rooftop greenhouses are not limited, but based on the characteristics of yield and favorable vegetable protection management, green leafy vegetables, tomatoes, vanilla, etc., can be prioritized [29].

5.3. Derivation of Calculation Formulas for Agricultural Production Potential on Roofs and Urban Spaces

Based on the previous analysis and calculation process, the following four calculation formulas were derived.

1. The first step was to obtain the roof inventory area of a certain city or region, which can calculate the annual production of vegetables grown on the roof of that city or region.

$$P_{\text{Annual yield of roof vegetables}} = S_{\text{Roof inventory area}} \times A \times Q$$
$$= 0.847 S_{\text{ Roof inventory area}} Q_{\text{Annual vegetable yield per unit area}} \tag{1}$$

P—Annual yield of vegetables grown on roofs of buildings in a certain city or region, unit kg;

S—The roof area of a city or area that can be used for agricultural cultivation, unit m^2;

A—Utilization rate of roof area, 84.7% (ratio of roof agricultural planting area to roof area);

Q—Annual yield of vegetables per unit area, which can be selected according to cultivation methods: soil cultivation can choose 4.78 kg/m^2, facility cultivation can choose 15.04 kg/m^2, and the mixed method of soil cultivation and facility cultivation can choose 9.91 kg/m^2.

2. The inventory is a time-consuming and labor-intensive work. If the conservative value of 5.81 ha/km^2 (5.81%) obtained from the inventory of the Shibei District of Qingdao is taken as the calculation basis, the annual production of vegetables grown on the roof of a city or region can be derived by knowing the size of its land area. The calculation formula is as follows:

$$P_{\text{Annual yield of roof vegetables}} = S_1 \times S_2 \times A \times Q$$
$$= 6.1 \times 10^4 S_{1\text{Urban land area}} Q_{\text{Annual vegetable yield per unit area}} \tag{2}$$

P, A, and Q are the same as Formula (1);

S_1—Land area of a certain city or region, unit km^2;

S_2—Roof area per square kilometer; the conservative value of 7.2 ha/km^2 (7.2%), which is obtained from the inventory, is taken here.

3. According to the above derivation process of roof production potential, we can know the annual production of vegetable planting and the amount of the population that can be supplied by a certain type of space (not limited to the roof) in a city or region. The calculation formulas are as follows:

$$P_{\text{Annual yield of vegetables}} = S \times A \times Q \tag{3}$$

$$N_{\text{The number of people that can supply the city}} = (S \times A \times Q)/C \tag{4}$$

Q can refer to Formula (1);

P—The annual yield of vegetables that can be grown in a certain type of space in a city or region, unit kg;

S—The area of a certain type of space that can be used for agricultural cultivation obtained from the inventory of a certain city or region, unit m^2;

A—Utilization rate of a certain type of space area (the ratio of available agricultural planting area to a certain type of space area after considering the occupation of space by roads, management, and facilities);

N—The number of urban population that can be supplied by the annual yield of a certain type of vegetables in a city or region, unit person;

C—Annual per capita vegetable consumption (refer to the data obtained in this article, 140 kg/year).

According to the China Statistical Yearbook 2022, the area of urban built-up areas in China is 62,420.5 square kilometers [30]. If calculated according to the usual ratio of 10–20% of the urban area, the usable roof area of urban built-up areas in China is 62,420–1,248,400 hectares. If the results of the roof inventory in the Shibei District of Qingdao are 7.2%, the available roof area in urban built-up areas in China is 449,400 hectares. Given the abundance of sloping roofs in Qingdao, the available roof area data are conservative. Based on the above, 624,200 hectares was selected as the available roof area in urban built-up areas. The planting method was selected with half facility cultivation and half soil cultivation and substituted into Formulas (1) and (4). Therefore, the available roof area in urban built-up areas in China can produce 52.39 million tons of vegetables, meeting the annual vegetable consumption of approximately 370 million people.

6. Conclusions

This article takes the roof space in the Shibei District of Qingdao as the research object. Based on the determination of roof inventory standards, GIS technology and remote sensing methods were used to conduct the idle roof space inventory. Combined with the annual yield of vegetables per unit area and the annual consumption standards of vegetables by citizens, yield and supply and demand calculations were conducted. The conclusion is that the idle roof area and the agricultural production potential in cities are relatively large. The research results indicate that the roof area of urban buildings in the Shibei District of Qingdao is 383.3 hectares, with an annual vegetable production potential of 25,800 tons, which can supply the urban population of 184,300. Based on the derived calculation formulas for roofs and urban space, it was further inferred that China's urban built-up areas can use roofs to produce 52.39 million tons of vegetables, which can meet the annual vegetable consumption of approximately 370 million people, and this quantity is also considerable.

In summary, in terms of rooftop agricultural production space resources, the research data show that there is a large stock of urban building rooftop space and a great potential for agricultural production. In terms of labor, technology, and other production factors, citizens and farmers entering cities in the process of urbanization can provide a certain amount of labor. The technology of roof agriculture planting is relatively mature, and there are currently many successful cases of roof farms and roof greenhouses. According to the relevant questionnaire survey, the proportion of intention to cultivate rooftop agriculture is the highest. Therefore, the development of rooftop agriculture is highly feasible, and it is recommended to prioritize the development of rooftop agriculture in the future. In addition, urban agriculture such as idle land agriculture and community agriculture has also been developed to some extent. It is recommended to gradually carry out urban spatial inventory of idle land, communities, parks, and other areas in the future to promote the development of urban agriculture.

Author Contributions: Writing—original draft, X.W.; Writing—review & editing, X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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