The potential for rooftop agriculture in the city of Rio de Janeiro: Growing capacity, Food security and Green infrastructure

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Abstract. The research explores the multifaceted benefits associated with the implementation of urban agriculture on roofs in Rio de Janeiro. The city has challenges in terms of food security, urban sprawl and the fragmentation of the green infrastructure. The study aims to look at rooftop agriculture as a multifunctional solution for addressing these concerns. The methodology consisted of: 1) LIDAR-based mapping and detection of all the roofs with an inclination inferior to 5 degrees on 69% of the surface of Rio de Janeiro City, 2) Analysis of the city structure and the key areas presenting a high flat roof potential, 3) Evaluation of the growing capacity of the flat roofs landscape and the yearly demand of vegetables in Rio de Janeiro City, 4) Visualization of the key locations for rooftop agriculture in the region of Bangu using parametric modelling. The research shows that 1,385 hectares of roofs would be suitable for rooftop agriculture within the study region. This productive roof surface could produce enough food to meet the yearly demand for vegetables of 39.2% of the inhabitants of the city of Rio de Janeiro. The study also demonstrates the great relevance of implementing rooftop agriculture in the poorest communities of Rio de Janeiro in the perspective of tackling food insecurity.

1. Introduction

Food is an essential element of our cities. However, planners do not usually integrate food production into urban design or city development [1]. According to a report published by the World Bank, 70 to 100% more food will be needed by 2050 [2]. In the context of Brazil, food security is an ongoing challenge: the current economic crisis and the unevenly distributed income increased the gap between the richest and poorest classes in the last years. As a result of insufficient incomes, almost a third of the Brazilian population does not have appropriate resources for acquiring appropriate quantity and quality of food [3]. By 2050, it is estimated that 68% of the world population will live in urban areas. In Brazil, up to 92% of the population is expected to settle in cities by the same year [4]. The vision of the New Urban Agenda of the UN-Habitat highlights that urbanization, if well-planned and well-managed, could be a powerful tool for sustainable development in countries. Food security and nutrition are at the core of sustainable urban development: a strong focus is made on the necessity to
go beyond the conventional separation between rural and urban spaces [5]. Urban agriculture could be one solution to provide fresh and affordable food close to the consumers in highly urbanized areas.

Cities should not only grow in size but also focus on developing their urban qualities in order to manage sustainable development. Strategic and sustainable plans are essential to cope with future urban challenges. Improving urban qualities requires a deep understanding of the city organization [6]. Accordingly, a well-designed green infrastructure is one key element for the urban system since it contributes to mitigating the negative effects of urbanization and supports urban resilience to environmental changes [7]. The UN Sustainable Development Goal 11 “Make Cities inclusive, safe, resilient and sustainable” underlines the importance of green spaces in urban areas, as inclusive spaces and supporting the improvement of air quality [8]. In highly urbanized areas, due to urban pressure and land speculation, vacant spaces are rare for the implementation of greenery. Exploiting structures such as roofs and building facades is an opportunity for consolidating the green infrastructure in urban centers.

With 1200 km² and 6.4 million inhabitants, the city of Rio de Janeiro is a complex and dynamic urban system in constant expansion [9]. The north-east of the metropolis is the densest urban area with very few green spaces and public squares. Throughout the city, several environments can be spotted: large tropical forests contrasting with heavily impervious and gray streets where most of the population lives. The city did not integrate landscape ecological processes and flows into its development, and hence threatening city biodiversity conservation and protection. The metropolis has also a chronic problem with floods as a result of the lack of sustainable planning in urban areas of low permeability [10]. Multifunctional rooftop agriculture provides a large range of environmental benefits: the enhancement of the green corridors network connectivity, the improvement of the air quality, the production of local food or the mitigation of the urban heat islands effect. The present research focuses on detecting the spatial synergies between the flat roofs landscape and the socially and environmentally vulnerable areas of Rio de Janeiro. By transforming unused flat roofs into productive spaces, the strategy consists of integrating urban agriculture into the key zones of the city.

2. Materials and Methods
The first step of the study aims to map the rooftop agriculture potential based on the roofs inclination and consequently, to reveal new space opportunities for the city of Rio de Janeiro. The objective is to quantify the number of flat roofs which could be converted into productive green spaces. Depending on the results of the mapping, the second step of the study intends to evaluate the growing capacity of the flat roofs landscape and consequently the number of inhabitants who could fully rely their vegetable consumption on rooftop agriculture. Adequate agriculture methods for the existing building typology will also be proposed. The last part of the paper presents a visualization of the green corridors network which could be potentially constructed using rooftop agriculture in the region of Bangu. The goal is to analyze the urban roofs landscape (supplied as GIS Geographic Information System data) and provide the possible locations and configurations for rooftop agriculture with respect to enhancement of the green network connectivity.

2.1. Lidar-based mapping of the rooftop agriculture potential
The collection of spatial data is performed through Light Detection and Ranging (LIDAR) technology. LIDAR is a laser-based remote sensing technology which calculates the distance to a target by illuminating it using laser light [11]. The Instituto Pereira Passos of the Rio Prefeitura provided the LIDAR data necessary for the study. This data is based on an evaluation of Airborne laser scanning from 2013 [12]. The laser scanned aerial survey provides a dataset with a point density of 2 points per square meter and a basis for the roof slope analysis. The survey did not cover the whole city but exclusively the areas of Rio de Janeiro in urban expansion, which represents 830,93 square kilometers (69.23% of the overall surface of Rio de Janeiro) as shown in figure 1 [13].
Figure 1. Area of Rio de Janeiro City covered by the LIDAR data survey in 2013 and used in the study.

Roofs were considered as suitable for rooftop agriculture when their inclination is less than 5 degrees. In order to calculate the angle of the roofs in Rio de Janeiro, it is necessary to first create a high-resolution Digital Terrain Model (DTM) and Digital Surface Model (DSM) (figure 2). The models were generated using LAStools with a pixel resolution of 0.25m². The Digital Surface Model was based on the first returns.

By combining the two output models, the second step of the study aims to calculate the roof slope using the GIS (Geographic Information System) Application QGIS (figure 3).

Figure 2. Data processing workflow for the generation of the Digital Terrain Model and the Digital Surface Model of Rio de Janeiro City.

2.2. The design of the green corridors network in the region of Bangu

The vertical dimension of habitats, such as green roofs, has been investigated by the project ENHANCE in Zurich. The results show that, despite their height, green roofs are valuable stepping stones for green networks and enable a higher permeability of the urban landscape for arthropod biodiversity. The roof size parameter does not have an effect on the community: even small green surfaces can provide a relevant space for urban biodiversity [14]. Recent research conducted on the city of Stockholm used graph theory to analyze pollinator’s dispersal power. The results demonstrate that the connectivity of urban green patches is the most important parameter for the resilience of the ecosystem [15]. In 2004, a study in Canada showed the relevance of plant diversity in urban gardens to increase the pollinators’ attraction potential [16]. According to the Institute for Ecosystem in Italy, green rooftops, if planned with diverse plants, are valuable for any biodiversity and prevent from habitat fragmentation caused by urban expansion [17].
Based on these observations, a parametric definition using Grasshopper (a graphical algorithm editor with Rhinoceros 3D modeling tools) was designed for the planning of green corridors network. Cluster 1, which covers the regions of Bangu, Vila Kennedy and Gerocino, was chosen for the case study. To optimize the existing green infrastructure, the study focused on enlarging the network by creating new bridges (or stepping stones) with the use of hypothetical rooftop gardens between the isolated green areas. The green corridors network was constructed as a minimum spanning tree: building up a set of edges connecting all green spaces such that the overall sum of the edge length is minimized [18]. The connecting distance of the green spaces was set to 500 meters since it represents a suitable flight foraging distance for most common bee pollinators [19]. The data used for the analysis of the green spaces distribution was the “Cobertura Vegetal e Uso da Terra” from 2014 provided by the Prefeitura Rio [20]. The height differences between the ground-level green areas and the flat roofs were not considered.

3. Results

3.1. Results of the mapping and analysis

The map includes all the flat roofs with a minimum size of 5 square meters and a minimum height of 2 meters. As a result, smaller areas are not reported as a potential. The map does not include the structural conditions of the roofs; this criterion requires an on-site investigation. The Lidar-based mapping shows that 1,384.5 hectares of flat roofs are available on the studied area of Rio de Janeiro City. Flat roofs represent 11.2% of the rooftops landscape. The results are mapped on a grid of 1 square kilometer which displays the sum of the flat roof surface for each cell. It is important to highlight that very high rooftop potential zones (defined as more than 64000 square meters per grid unit) are exclusively in areas where the population density is high or very high (more than 12000 hab/km²). This shows that rooftop agriculture could be targeted in these key zones and benefits to a high density of consumers within a relatively short distance, providing local and fresh food directly to the households.

The analysis of the present paper focuses on four clusters, evaluated as key zones with the highest potential of flat roofs: cluster 1 - with Bangu, Senador Camara, Gericino and Vila Kennedy; cluster 2 - with Magalhães Bastos, Padre Miguel and Realengo; cluster 3 - is Cidade de Deus; cluster 4 - with Cosmos and Inhoaiba (figure 4).

![Figure 4](image)

Figure 4. Clusters as key areas for rooftop agriculture in Rio de Janeiro City according to the mapping results.

These four clusters represent 355,44 hectares of flat roofs, which corresponds to 26% of the overall flat roof potential which was detected during the Lidar-based mapping. Land uses are mainly residential, including “favela” areas which are shaped with numerous blockhouses and small flat roof terraces. Other land uses with a high amount of flat roofs are commercial and services areas (such as Shopping Bangu), industrial areas (large single flat roofs units) and zones with public infrastructures (such as the prison complex in the north of Bangu). The Social Development Indexes - IDS (combining indicators of educational level, income, housing quality and level of basic sanitation) of the cluster regions are among the last third of Rio de Janeiro City with 0.545 for Realengo or 0.478 for
Inhoaiaba [21]. Therefore these highly populated zones with a great flat roof potential correspond to areas with high social vulnerability. Holding the highest flat roof potential of the study, these zones could benefit greatly from rooftop agriculture. Table 1 gives an overview of the building characteristics and the roofs typologies observed in the cluster regions.

| Clusters | Building characteristics | Flat roof dimensions |
|----------|--------------------------|----------------------|
| 1,2,3,4  | Mean value of the building height: 4.5m | Minimum flat roof: 5 m² |
|          | Median value of the building footprint area: 71.4m² | Largest flat roof: 6,142.8 m² |
|          | Typology: Mostly single to 2-story houses | Median flat roof area: 14.31 m² |

The most common building typology corresponds to single to two-story building blocks, with a height of 4.5 meters and a median building footprint laying around 71.4 square meters (figure 5). Low building height is an important parameter for maximizing the impact of the rooftop gardens since it creates a more homogeneous roofs landscape which is closer to the existing green infrastructure on the street level.

![Image](a) ![Image](b)

**Figure 5.** Rio de Janeiro City: (a) The roofscape of Cidade de Deus; (b) Front view of building blocks in Realengo. [22]

The building structures are usually composed of concrete pillars and the floors are floor beams and slabs. The rooftop terraces are covered by a corrugated iron roof or left open. Water tanks may be placed on the roof to provide running water. The houses are often constructed over years: the first two floors may be completed in the future by an extra floor for rental to a family member or an external person [23]. For this reason, the structure conceived is robust in the perspective of a vertical extension. This constitutes a great opportunity since the structural conditions of the building have a strong impact on the implementation costs of the rooftop gardens.

The suitable agriculture typology for the individual houses would be informal rooftop agriculture since the roofs are essentially private with a low median area of 14.2 square meters. Simple production systems could be implemented such as small containers, boxes or bags filled with soil and compost. The small gardens would enrich the diet of the families with fresh vegetables and save on food expenditure. Nonetheless, rooftop gardens are not only valuable for food production but can also benefit the community. The larger flat rooftop surfaces located on public buildings could be transformed into community garden hubs, serving as a platform for the neighborhood activities and increasing food education. Roof greening policies should be addressed particularly within the four clusters since these areas hold a great flat roof potential, a low amount of green areas and low social development indexes.

**3.2. Growing capacity and food security**

The yearly vegetable requirement in Brazil was based on official statistics collected by the “Food and Agriculture Organization of the United Nations - FAO” and published in 2017 [24]. The database FAO Hortivar was chosen as a reference for the evaluation of the vegetable production yield of rooftop agriculture. The production yield of the rooftop agriculture systems fluctuates according to the vegetable species and the agricultural techniques. The productivity of the plant species cabbage is 20
kg/m²/year, corn salad 14.6 kg/m²/year and eggplant is around 16.9 kg/m²/year [25]. For the research, the production yield of the rooftop gardens is set to 15 kg/m²/year. This value seems realistic compared to several project results which resulted in a productivity yield of 15.2 kg/m²/year in Bologna, 18 kg/m²/year in Cuba and up to 50 kg/m²/year [26-28]. To calculate the net production surface of the roofs, it is estimated that 35% of the overall surface is used for infrastructural spaces, as suggested in a recent study for the city of Bologna [26].

The national and World Health Organization recommends between 73 to 91.5 kilograms of yearly vegetable intake per capita. Brazil is below this recommendation, with only 50.3 kilograms [24]. Accordingly, the entire rooftop surface could produce around 134,985 tons of vegetables per year, which represents 39.2% of the evaluated vegetable requirement of the city of Rio de Janeiro (Table 2).

Table 2. Estimation of the potential productivity of the flat roofs landscape based on the mapping results for Rio de Janeiro City [9, 24, 25]

| Element                                       | Value       | Unit                  |
|-----------------------------------------------|-------------|-----------------------|
| Overall roof surfaces                         | 12,354.1    | ha                    |
| Flat roofs                                    | 1,384.5     | ha                    |
| Ratio of flat roofs                           | 11.2        | %                     |
| Net production surface of the rooftop garden | 899.9       | ha                    |
| Productivity yield of the rooftop gardens     | 15          | kg.m⁻².year⁻¹         |
| Potential vegetable production                | 134,985     | t.year⁻¹              |
| Average yearly vegetable consumption per capita| 51.5        | kg                    |
| Potential vegetable consumption per capita    | 91.5        | kg.year⁻¹             |
| The estimated population in Rio de Janeiro City (2018) | 6,688,927  | persons               |
| Overall vegetable demand in Rio de Janeiro City | 344,680.4  | tons.year⁻¹           |
| Potential of persons fed per year in Rio de Janeiro City | 39.2       | %                     |

Rooftop gardens in the city of Rio de Janeiro could be a valuable contribution to food security as well as providing other benefits such as improved city liveability and community building. It would stimulate better food education and provides fresh vegetables directly in and by the households.

3.3. Modeling the green corridors network

Cluster 1, which covers the regions of Bangu, Vila Kennedy and Gerocino, is characterized by a scattered green infrastructure and a high flat roof potential of 158.8 hectares according to the results of the Lidar-based mapping. The existing green corridors network links the two large green areas (the forest of Bangu North and the Parque Estadual da Pedra Branca in the south) with several green patches and a long river stripe. Connecting every green patch with a flight foraging distance of 500 meters results in a green corridors network of 67.1 kilometers (figure 6).
Figure 6. Results of the green corridors network mapping of cluster 1 (a) Distribution of the green areas in cluster 1; (b) Existing green corridors network connecting green areas within 500 meters distance of each other.

Mostly scattered and thin, this network could be substantially densified with the use of rooftop gardens. The parametric model estimates that greening all the roofs with a flat surface larger than 100 square meters (which represents 1064 roofs), would extend the existing network with an extra length of 77.2 kilometers. The network would be 2.15 times longer than the initial one and would sprawl across a larger region (figure 7).

Figure 7. (a) Overlapping of the flat roofs landscape with the existing green corridors network; (b) Potential green corridors network using the flat roofs larger than 100m².

The visualizations give the basics of a reflection on how rooftop gardens can be linked to the existing green corridors network and enlarge the urban biological system of Rio de Janeiro City. Since the definition of the model is parametric, it is possible for planners to generate other networks by setting differently the two following parameters: the size and the number of flat roofs and the flight foraging distance (thus the type of pollinator considered). The increase of connections between the green patches would allow a higher dispersion potential of the urban biodiversity.
4. Discussions
The study outputs should be considered as a support for decision-making in planning urban green infrastructure. The results aim to increase awareness about the potential for rooftop agriculture in Rio de Janeiro. The map is not only directed to policy-makers and city planners but also property owners who could start a dialogue with greening experts and potential farm tenants. From 2019, the map will be available on the platform “Sistema Municipal de Informações Urbanas SIURB.rio”.

The cultural parameter is an important criterion for the long-term and extensive implementation of agriculture on roofs. Flat roofs in Rio de Janeiro City are valuable for building owners and the advantages of possessing a rooftop garden are not widely acknowledged by the population. Therefore the promotion of successful cases on public buildings (schools, institutional buildings, and others) and in communities would expose the multifaceted benefits offered by the green structures and could generate a contagion effect. In the key zones with a high density of small flat roofs such as the “favelas” of Rio de Janeiro, the research shows great social and environmental potentials. However, the difficulty of access, the violence and the mistrust of the population towards city officials have to be considered. A bottom-up approach is strongly recommended. Community-based and grassroots actions is a key factor for the long-term implementation of garden projects.

Adequate financial and incentive policies are also essential for convincing building owners to install intensive greening or agricultural systems on their roof. The “QualiVerde” is an incentive program which promotes sustainability actions including the implementation of green roofs for new and existing constructions [29]. The certification is optional and grants tax benefits to the qualified projects. This is a progressive first step towards integrating agriculture into the roofs landscape of Rio de Janeiro.

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