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# Quantifying the City's Green Area Potential Gain Using Remote Sensing Data

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**Abstract:** Information about green spaces available in a city is essential for urban planning. Urban green areas are generally assessed through environmental indicators that reflect the city's quality of life and urban comfort. A methodology based on 3D measure and analysis of green urban areas at the city scale is presented. Two products are proposed: (1) measuring current vegetation cover at ground level through object-oriented classification of WorldView-2 imagery; and (2) estimating potential green cover at rooftop level using 3D data obtained by LiDAR sensor. The methodology, implemented in Lisbon, Portugal, demonstrates that: (1) remote sensing imagery provides powerful tools for master planning and policy analysis regarding green urban area expansion; and (2) measures of urban sustainability cannot be solely based on indicators obtained from 2D geographical information. In fact, 2D urban indicators should be complemented by 3D modelling of geographic data.

**Keywords:** green urban areas; LiDAR; green roofs; GIS

## 1. Introduction

Ecosystem services provided by green urban spaces have been an important issue in urban planning and public policy for some years [1,2]. Nevertheless, while international efforts have been more concerned with preserving large, bio-diverse and relatively untouched ecosystems, less attention is being paid to the type of natural spaces that are close to where people live and work: the city's small green areas [3].

Lack of vegetation in cities is one of the factors contributing to the increase of urban temperatures [4]. Covering roofs with vegetation—i.e., green rooftops—helps to mitigate the urban heat island effect by modifying not only the buildings' microclimate but also the local climate of the city [4–9]. Green roofs offer many other public and private benefits. Public benefits include the promotion of biodiversity, reduction of stormwater runoff, lessening of air pollution and improved urban comfort [10–14]. Private benefits include energy savings by decreasing indoor cooling load demand, noise attenuation, longevity of the waterproof membrane and green space available for recreation [4,15–17].

Policy makers have already recognized green rooftops as an effective planning tool. In fact, and in order to stimulate the wider implementation of green roofs in the cities, local governments in many countries are offering various forms of sponsorship: (1) direct financial incentives (e.g., Berlin, Germany); (2) reduced stormwater taxes (e.g., Philadelphia, PA, USA); (3) considering green roofs as a measure of ecological compensation for new building projects (e.g., Singapore), or (4) integration into local land-use plans (e.g., Munich, Germany) [18–20]. Among European countries, Germany has the highest rate of conversions from conventional roofs to green roofs. The development of green roofs started back in the 1960s and has spread to other countries. In Munich, Germany, there is an obligation to landscape all suitable flat roofs with a surface area of over 100 $m^2$. In the Danish capital, Copenhagen, all new suitable roofs with a pitch of under 30° are to be landscaped [18]. The Austrian city of Linz requires green roofs on all new residential and commercial buildings with rooftops larger than 100 $m^2$. France has decreed that all rooftops on new buildings built in commercial areas must either be partially covered in plants or solar panels [21]. Outside Europe, there are also initiatives to promote green roof retrofits. In Toronto, Canada, the Municipal Code has stipulated that since 2010 all new commercial, institutional and residential developments with a minimum Gross Floor Area of 2000 $m^2$ must have a green roof, and since 2011 all new industrial developments must have them as well [22]. In Portland, Oregon, the municipality mandates that all new city-owned facilities shall include a green roof with 70% coverage unless it is impractical [23].

At the city scale, the contribution of available ground and rooftop areas needs to be taken into account when considering alternative approaches to increase green urban areas. This situation is particularly important in urban contexts where the land available for extra natural covering is a rare commodity [24–27]. Such information on suitable locations is essential for urban design and planning, but also to make informed decisions towards urban sustainable development. For the city scale, a detailed multi-sensor data analysis is required in order to produce efficient map-based tools. Typically, land cover maps at local scale are based on 2D imagery processing. Recently, some countries, such as Spain, Denmark, Finland or the United Kingdom, already make provide open access to airborne laser scanning data. Providing users with medium-sized 3D data (high density point clouds over one point per $m^2$) shall empower researchers and public institutions with recent and updated high quality information and thus facilitate the estimation of green urban areas. In this context, an analysis based on Geographic Information Systems (GIS) is proposed to characterize spatially-related variables within a digital environment.

In the present study, the green urban area is evaluated at the city scale for Lisbon, the capital of Portugal. A large-scale analysis is performed, taking two levels into consideration: ground and rooftop (Figure 1). For the ground level, a vegetation mapping is obtained through Very High Resolution (VHR) image classification, and corresponds to the current green area of the city. The contribution of rooftops towards the total green open space is assessed using a 3D building model based on Light Detection And Ranging (LiDAR) data and VHR images. This approach allows for a detailed estimation of available roof areas since the physical aspects, such as slope, orientation, and shadows cast by surrounding buildings and topography, are calculated for each building in the area. Results are presented in scenarios: on the one hand, taking into consideration the current vegetation cover at the ground level, and on the other, estimating the potential cover area on rooftops, according to different geographical criteria.

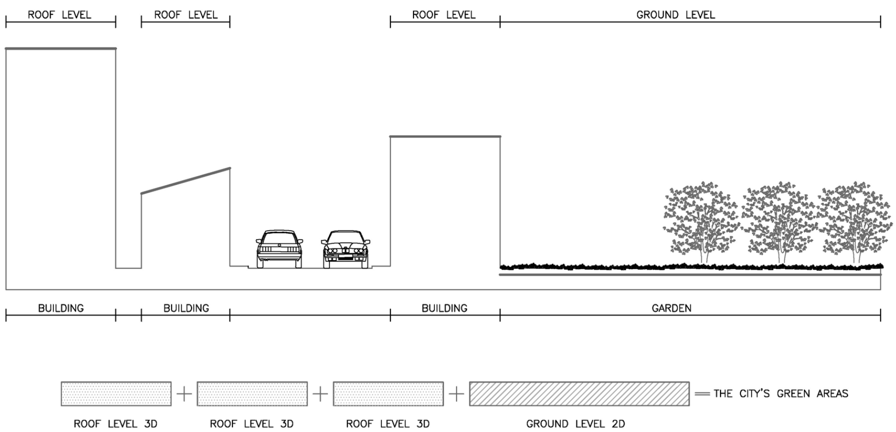


**Figure 1.** The city's green area calculated in two levels of analysis: ground and rooftops.

In a similar study, Mallinis et al [28] proposed a methodology based on GEographic Object-Based Image Analysis (GEOBIA) to estimate green roof retrofitting areas using VHR orthoimages and a Digital Surface Model (DSM). Where roofs had no tiles, the available area and presence of shadows (based on the spectral information available in a single-date image) were the assessed variables. The result is a quantification of the total green urban area possible if green roofs were implemented widely. Wong and Lau [29] conducted a preliminary research on green roof retrofit potential in the densely occupied old urban district of Mongkok in Hong Kong. Focus group discussions and simulation models were developed for a small pedestrian area. Only two variables were analyzed: exposure to sunlight and roof space. A virtual 3D model of the buildings was developed and sun-path was simulated. Furthermore, Google View images were also used to manually identify the roof areas with existing rooftop plant and equipment. The modelling process suggested that while many of the rooftops have the potential for green roof retrofit, some of the roof areas were not suitable because of inadequate exposure to sunlight and unavailability of free space. Tian and Jim [30] have studied the factors that influence the spatial pattern of sky gardens in Hong Kong, using orthophoto maps, the buildings' footprints, and the zoning plans. Buildings were classified according to the number of stories, height, area, density and spatial pattern, and evaluated at district level. The results indicate that: (1) booth rooftops and podiums were not adequately used for green spaces; and (2) morphological indicators like building density, number of stories and podium area play an important role in its spatial distribution. The aim of this study was to study current green rooftops and podiums and rather than attempt to quantify the potential for new green roofs was made.

In an urban environment, analyzing potential candidates for green retrofit crucial variables need to be taken into consideration including roofing material, available area and sunlight exposure. In addition, roof slope must also be evaluated. Although any pitch of roof can be greened, high slope surfaces, however, require additional support to avoid vegetal material slippage and have limited access for maintenance. Consequently, high pitched roofs require a complex design, with increased cost. In an initial assessment of a city's potential for green roofing, high slope roofs should be dismissed. Nevertheless, roof slope was not one of the variables taken into account in previous studies. Furthermore, the individual impact of each criterion was not considered in the selection of candidates for green roofs and criteria adjustments were not foreseen or quantified. Also in the above-mentioned studies, no attempted was made to provide urban planners and city decision-makers with alternative scenarios on potential green roofs.

Going beyond previous studies, the methodology proposed in this study is a follow-up of a previous research project developed by Santos et al. [31], concerning the best rooftops for the installation of a solar system. The technical originality of this research project lies in the effective mapping tool designed for decision-making support. Detailed scenarios that quantify the increase in the city's green area according to roof covering material, area, slope and sunlight criteria are made available. These findings can support urban planners and influence policy incentives to target suitable buildings.

Furthermore, this study innovates when information retrieved from 3D geographical modelling is added to a 2D analysis. This is achieved by estimating the potential gains in terms of green areas at the local scales, considering suitable rooftops. The methodology is straightforward and transferable to other Mediterranean cities.

## 2. Study Area and Materials

### 2.1. Study Area

Lisbon is the capital of Portugal, with a population close to 550,000 residents (2011 official census) (Figure 2). Located in the Atlantic coast of Portugal, the city is characterized by a Mediterranean climate, with an average of 8 hours of sunshine per day [32]. Lisbon occupies 85 km$^2$ and is located on the North bank of the Tagus River with approximately 20 km of riverfront. The Monsanto Forest Park is the largest green urban structure (1000 ha), linked to other green urban spaces in the city via a green corridor. Lisbon has a great diversity of green urban spaces, from arborized open squares, to tree alignments, public parks, communal gardens, and internal courtyards. The building environment is much diversified, and includes a mix of single homes (with one or two stories), apartment buildings (four up to ten stories), and multi-story commercial and mixed-use buildings.

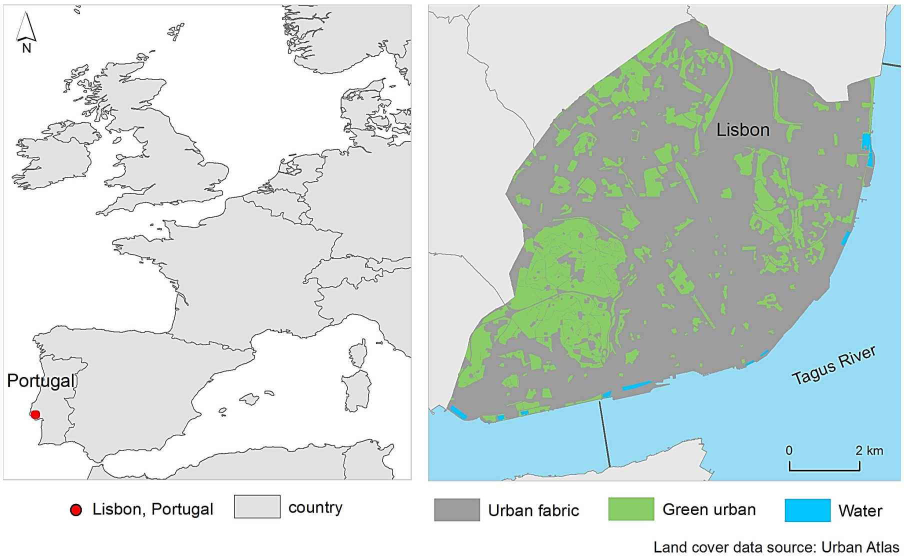


**Figure 2.** Study area: Lisbon, Portugal.

Vegetation per capita is an indicator that can be used to infer the quality of life in Lisbon. Based on official data [33] of (1) the resident population retrieved from the Urban Audit data collection system; and (2) the "green urban areas" class from the Urban Atlas, a per capita value of 24 $m^2$/inhabitant was obtained for Lisbon (Table 1).

**Table 1.** Demographic data and green area for Lisbon, Portugal.

| City | Population 2008 | Pop. Density (Pop/km$^2$) | Green Urban Areas (m$^2$) | Vegetation per Capita (m$^2$/Inhab) |
|---|---|---|---|---|
| Lisbon | 489,562 | 5778 | 11,914,531 | 24 |

Within the Biodiversity Strategy, Lisbon City Council included in its new Master Plan a series of sustainable measures aiming to increase the green structure rates available in the city [34]. In 2013, the Lisbon City Council identified 21 green roofs, totaling 52,085 $m^2$.

## 2.2. Materials

Planimetric and altimetric datasets were used to characterize vegetation at the city scale (Figure 3). Planimetric information includes a VHR image and a map retrieved from municipal cartography. A WorldView-2 image (WV-2) was acquired on 29 June 2010, covering the city of Lisbon with an off-Nadir angle of 7.1° (Table 2). Available in Ortho Ready format, this image has a spatial resolution of 2 m in multispectral mode (8 bands), a pixel size of 0.5 m in panchromatic mode, and a radiometric resolution of 11 bits. The pre-processing included image pan sharpening, following an algorithm developed by Zhang [35], and image orthorectification in order to reduce geometric distortions introduced by the terrain. Afterwards, a Normalized Difference Vegetation Index (NDVI) image [36] was produced to integrate the dataset for vegetation extraction.

Planimetric data also includes the buildings' footprints retrieved from a 1:1000 Lisbon Municipal map from 1998, and updated in 2006 [37]. The altimetric set consists in 3D information obtained from a Light Detection And Ranging—LiDAR flight, that covered Lisbon in 2006. From the original

LiDAR point cloud (with a density of 1–2 points per m$^2$), a surface image was produced based on the 2nd return, with 1 m resolution. This image represents the DSM of the city.


**Figure 3.** Planimetric and altimetric data used for 2D and 3D analyses at the city scale.

**Table 2.** Characteristics of the WorldView-2 image used for local analysis.

| | | **Image Bands** | **Spectral Range (nm)** |
|---|---|---|---|
| Acquisition date | 29 June 2010 | 1 | 400–450 (coastal) |
| Sun azimuth | 140° | 2 | 450–510 (blue) |
| Sun elevation | 71° | 3 | 510–580 (green) |
| Satellite azimuth | 238° | 4 | 585–625 (yellow) |
| Satellite elevation | 82° | 5 | 630–690 (red) |
| Off-Nadir view angle | 7.1° | 6 | 705–745 (red edge) |
| Cloud cover | 0% | 7 | 770–895 (near IR-1) |
| Collected GSD | Pan 0.47 m, MX 1.88 m | 8 | 860–900 (near IR-2) |
| Product pixel size | Pan 0.5 m, MX 2 m | Pan | 450–800 |

## 3. Methods

A two-fold methodology was adopted to model vegetation at the ground level (2D analysis) and on rooftops (3D analysis). All processes were implemented in ArcGIS 10 (ESRI) software (Redlands, CA, USA). A framework is presented in Figure 4. From the 2D analysis, the current vegetation cover at the ground level was assessed. From the 3D analysis, the potential vegetation at rooftop level was estimated.

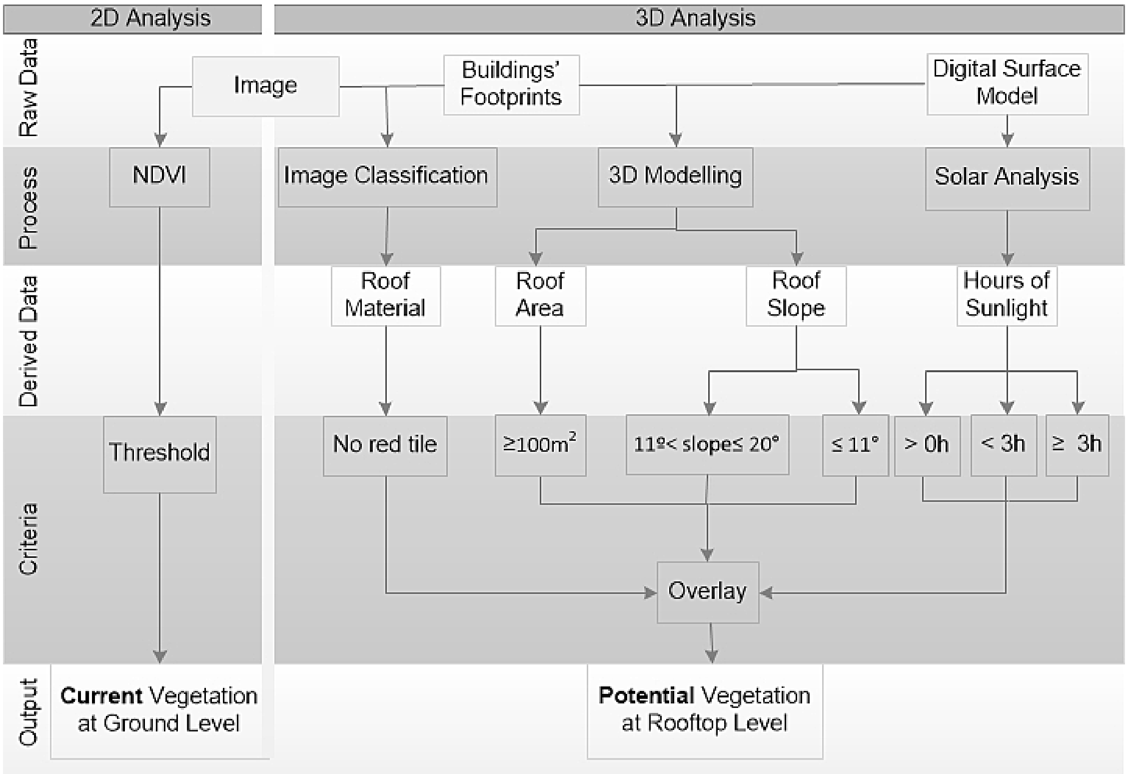


**Figure 4.** 2D and 3D analyses at the city scale.

### 3.1. Quantifying Current Ground Cover Vegetation

In order to assess the vegetation at the ground level, a 2D analysis was implemented using the Normalized Difference Vegetation Index (NDVI) image obtained from WorldView-2 imagery. NDVI is one of the most widely used indexes obtained from remote sensing data with high performance for vegetation mapping [38]. NDVI was calculated using Red and Near Infrared1 (NIR1) bands from the WV-2 dataset (Equation (1)). The NIR2 band was also explored, but the image did not capture photosynthetic activity as well as the one obtained with NIR1.

$$\text{NDVI} = (\text{NIR1} - \text{RED})/(\text{NIR1} + \text{RED}) \quad (1)$$

In order to identify current vegetation in Lisbon, a NDVI threshold of 0.03 was proposed. This value was obtained based on a visual analysis. The NDVI classification results in 2D information, i.e., ground cover vegetation. In order to assess the map's quality, an error matrix was populated based on reference data produced by an independent photo-interpreter, and quality indexes like overall accuracy, omission and commission errors were calculated.

### 3.2. Evaluating Rooftop Suitability to Receive Green Cover

To estimate the potential vegetation on rooftops, a 3D analysis was performed using the buildings' footprints and the DSM, together with the WorldView-2 image. This image was used to classify the roofs' covering material. This was a pertinent step because red tiled roofs are not usually suitable for green roof applications due to an initially high investment in tile removing and rooftop adaptation. Besides the covering material, the green roof retrofit potential depends on the physical aspects of the roof, such as available area and slope. Furthermore, in urban areas, the local built environment also plays an important role due to the shadowing effects of the surrounding buildings. These effects are essential when selecting the most appropriate plant species, and can be modelled at this exploratory stage.

Taking these aspects into consideration, several scenarios for the evaluation of rooftop suitability to receive vegetation were considered. After selecting those non-tiled roofs, with appropriate area and slope, two criteria were tested: roof slope and sunlight availability. The goal was to identify as many locations as possible, taking into consideration the choice of suitable plants, from sun-tolerant to intolerant ones that shall occur at the project stage.

Other requirements include adequate roof load bearing capacity, drainage conditions or waterproofing membrane type, which will not be considered in this research.

### 3.2.1. Rooftop Covering Materials

Roof covering materials were assessed in an object-oriented classification process. Our goal was to identify the city's tiled and non-tiled roofs, and disregard the former from further analysis. In this step, WV-2 images and the buildings' footprints were used. Derived from an object-oriented classification, the spectral information available in the image allowed us to separate red tiles from other roof covering materials. Feature Analyst 5, an extension of ArcGIS 10 (ESRI), was the selected classifier. Feature Analyst (FA) is a GEOBIA application that conducts an internal "hidden" segmentation of the image allowing for the classification and extraction of only those features that belong to the class of interest [39]. Spatial context is used by FA for this classification, using a parameter known as Input Representation. Input Representation determines the shape and size of the window used by FA to analyse each pixel. Based on the defined learning settings, the classifier uses characteristics such as spectral response/colour, size, shape, texture, pattern, shadow, and spatial association, to find features that are similar to the ones defined in the training set. In an FA supervised approach, this set is obtained by manually digitizing features of interest and should contain enough examples to account for feature spectral diversity and size. In order to reduce commission errors, the buildings' footprints were used as a classification mask, and the output was a map with the city's roofs without red tiles.

### 3.2.2. Rooftop Area, Slope, and Sunlight

The physical characteristics of the rooftops, such as area and slope, were modelled using the altimetry from the DSM and the location from the buildings' footprints.

The last criterion—available daily sunlight—was obtained with ArcGIS (ESRI)'s Solar Radiation analysis tools. This software allows the modelling of atmospheric effects, as well as site latitude and elevation, steepness (slope) and compass direction (aspect or orientation), daily and seasonal shifts of the sun angle, and effects of shadows cast by surrounding topography. As inputs, Solar Radiation requires the local annual average of beam and diffuse irradiation. As a result, a map with the incident global solar radiation at each pixel was produced. Subsequently, the sunlight availability at rooftop was evaluated using the Angström-Prescott formula (Equation (2)) (ratio of daily solar radiation to extra-terrestrial daily solar radiation vs. ratio of sunshine duration to day length) [40,41].

$$H/H_0 = a + b\ (n/N) \quad (2)$$

where H and $H_0$ are, respectively, the monthly mean daily global radiation and the daily extraterrestrial radiation on a horizontal surface; n and N are, respectively, the monthly average daily sunshine duration and the monthly average maximum possible daily sunshine duration; and a and b are empirically determined regression constants.

### 3.2.3. Selection of Rooftops with Potential to Be Used as Green Roofs

Based on the physical characteristics of the rooftops and on solar availability, several criteria were applied to identify suitable roofs. Regarding covering materials, only rooftops without red tiles were considered for further investigation. From this set, following the guidelines used in Munich (Germany) [18] and Linz (Austria) [42], the area criterion was applied: only roof areas over 100 $m^2$ were selected.

Another important aspect is roof slope. Although any pitch of roof can be greened, surfaces over 45° require additional support, complex design, and increased cost and limited access for maintenance. For land planning purposes, two scenarios to evaluate the city's green roof potential were tested. This approach identifies rooftops according to intervention cost-effectiveness, providing urban planners with different investment choices. A more conservative scenario considers flat rooftops—Flat Green Roof Scenario—and includes roofs with slopes less or equal to 11°. This scenario requires a lower initial investment in roof infrastructures, as indicated by the Toronto Green Roof Construction Standard [22]. The second scenario considers pitched roofs—Pitched Green Roof Scenario—with slopes less or equal to 20°. Such areas require protection against soil erosion and extra roof layers for waterproofing. The Pitched Green Roof Scenario demands higher investments to avoid plant and soil slippage.

Both scenarios can further be characterized regarding sunlight availability. This information can also be used to prioritize investments. Shadowing conditions are important in the project phase and can serve as guidance for plant selection. Based on the sunlight criterion, three situations were considered: sunny roofs, shaded, and sunny to shaded roofs (i.e., disregarding sun availability). Sunny roofs were identified considering a rule of thumb of 3–4 h of sunlight per day as a requirement for plant growth [29,43]. In this situation, landscape architects can select from sun- to shade-tolerant plant species (e.g., *Lavandula luisieri*, *Sedum album* or *Sedum ellacombianum*). Shaded roofs, on the contrary, are those that receive less than 3 h of sunshine per day. In this situation, landscapers can choose plant species according to the shadowing conditions (e.g., *Vinca minor* or *Vinca difformis*). The third option is considering all sunlight conditions, i.e., sunny to shaded roofs that can receive from full sun-tolerant to full shade-tolerant plants.

After applying these constrains, the potential green roof area of the city was estimated.

## 4. Results and Discussion

### *4.1. Mapping Vegetation at Ground Level*

To measure vegetation at ground level, an NDVI image from the summer period obtained from WV-2 imagery was constructed. The next step included threshold selection based on a visual analysis to classify all vegetated cover available in the city (NDVI value of 0.03). As a result, a map depicting vegetation at ground level was produced. This map indicates the existence of 25,835,522 $m^2$ of vegetation in Lisbon. This value is very different from the one reported in the Urban Atlas (11,914,531 $m^2$) (Table 1). This situation can be explained by four factors. Firstly, the difference is mainly due to the fact that the Urban Atlas (UA) uses a nomenclature based on Corine Land Cover, which gives priority to land use over land cover. Conversely, the classification of remote sensing data reports land cover. Secondly, the different minimum mapping units (2500 $m^2$ for UA vs. 0.25 $m^2$ for WV-2) compromise direct map comparison. Thirdly, private gardens or agricultural land are not included in the "green urban areas" class. Lastly, the NDVI indicates the presence of chlorophyll, and therefore is a more precise map than the one resulting from image classification. These facts result in different class areas, when comparing the two maps.

Afterwards, the map's quality was evaluated in a smaller area (Alvalade parish, with 534 ha). A reference map was produced based on the manual photo-interpretation of the WV-2 imagery [44] since no auxiliary information was available for the same period (2010) and with the compatible spatial detail. Then, in an overlaying process, reference areas were compared with classified ones. From this comparison, an error matrix was populated and quality indexes, such as overall precision, omission and commission errors were calculated (Table 3). Quality metrics revealed a good agreement, with an overall accuracy of 91%. Regarding the vegetation class, 18% was overestimated (commission error) while 12% was omitted (omission error). These errors occurred in places with sparse vegetation (commissions) and in vegetation shaded areas (omissions).

**Table 3.** Accuracy results of vegetation at ground level map.

| | Reference | | |
|---|---|---|---|
| **Classification** | **Vegetation** | **Non-Vegetation** | **Total** |
| Vegetation | 1,360,752 | 288,784 | 1,649,536 |
| Non-Vegetation | 177,130 | 3,515,424 | 3,692,554 |
| Total | 1,537,882 | 3,804,208 | 5,342,090 |
| | Commission Error | Omission error | |
| Vegetation | 18% | 12% | |
| Non-Vegetation | 5% | 8% | |
| Map | Overall Accuracy: 91% | | |

### 4.2. *Modelling Vegetation at Rooftop Level*

Based on the buildings' footprints, the total roof area was calculated. These building rooftops account for 19% of the total surface of Lisbon. These areas, usually overlooked by planners, can be used to mitigate the impact of the urban heat island or to beneficiate the buildings' energy performance, providing passive cooling to the built environment.

In order to consider a roof suitable for retrofitting, several physical attributes were taken into consideration: roof covering material, area, slope, and solar radiance.

#### 4.2.1. Rooftop Covering Materials

In Mediterranean cities in general, and in Lisbon in particular, tiles are the most common covering material for roofing systems. However, this is not a suitable covering for green retrofit, so the first step was to separate tiled roofs from other materials. The Feature Analyst's supervised mode was selected, and 36 training areas were manually digitized and identified for the "red tile" class. These areas represented red tiles in different shadowing conditions, and ranged from old to more recent tiles. For the learning process, the selected parameters were: Manhattan 5 algorithm, minimum area of 10 $m^2$, and the buildings' footprints as a classification mask. The Manhattan pattern is a solid pattern indicated for block-type features (such as roofs) that uses the value of immediate neighbour pixels to classify the central pixel [45]. Manhattan 5 uses a diamond shape pattern with a five-pixel width.

WV-2 imagery, due to the off-Nadir look angle (7°), causes the displacement of the roofs of taller buildings and consequently the misalignment with the respective footprint. This situation has already been reported in similar studies with VHR sensors [46–48]. As a consequence, some non-tiled roofs were partially classified as tiled in boundary areas, where adjacent tiled roofs existed (Figure 5). In order to minimize those situations, buildings with 85% of the area classified as "without tiles" were selected as retrofitting candidates. From the initial set of 62,935 buildings in Lisbon, only 13,005 where classified as non-tiled roofs.


**Figure 5.** Detail of red-tiled roof classification.

4.2.2. Rooftop Area, Slope, and Sunlight

The next step included calculating each roof area, slope, and available sunlight. Two inputs were required: the buildings' footprints and the DSM. From these data, roofs with slopes less or equal to 11°, and roofs with slopes ranging from 11° to 20° were identified.

Solar radiation available on each rooftop was estimated using the Solar Radiation analysis tools in ArcGIS. Using a methodology proposed by Santos et al. [31], the annual global solar radiation (direct + diffuse) was calculated for each roof (MWh/$m^2$ per year), using local monthly diffusion and transitivity parameters. Subsequently, the average daily solar insolation was assessed (Wh/$m^2$ per day). Using the Angström-Prescott formula, the corresponding monthly average sunshine duration was calculated for each roof and the three hours of sunlight criterion was applied.

4.2.3. Rooftops with Potential to Be Used as Green Roofs

Following slope criteria, flat and pitched green roof scenarios were tested (Table 4) (Figure 6).

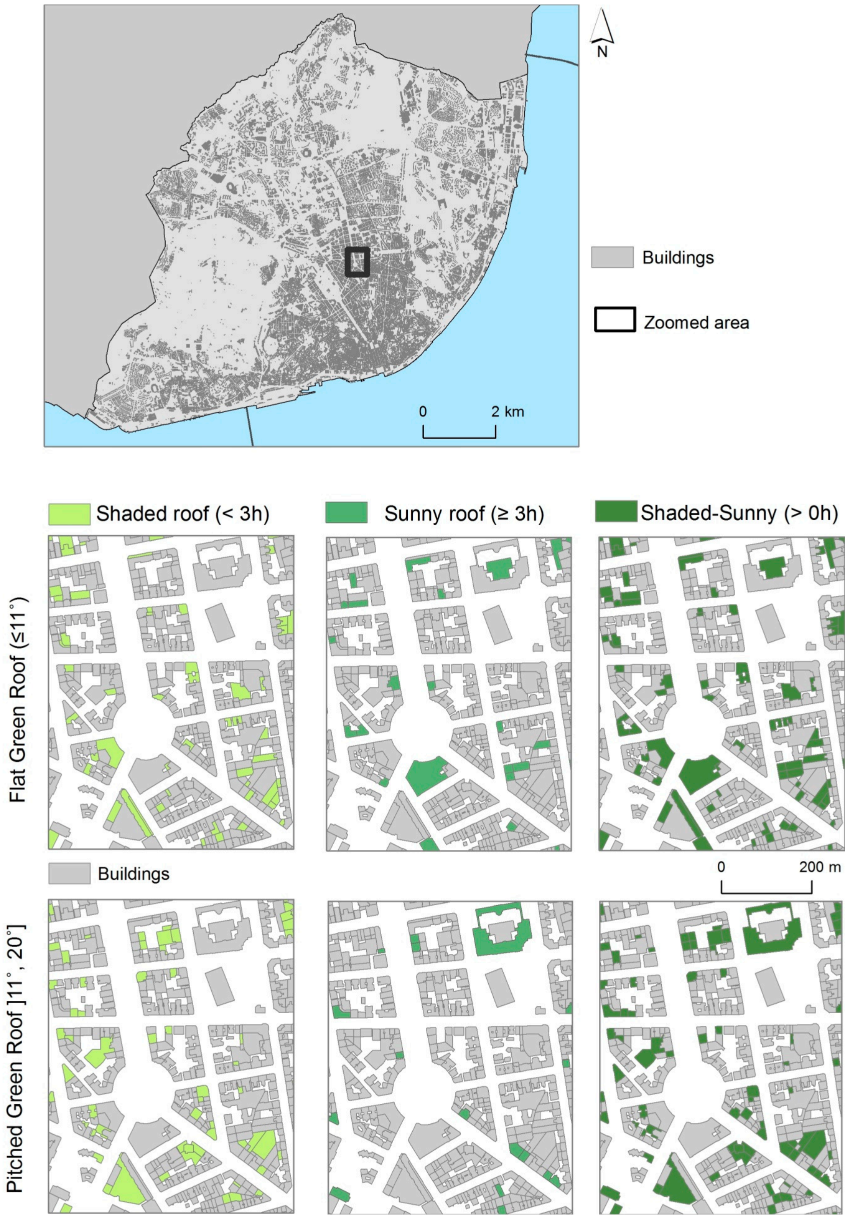


**Figure 6.** Potential green area at rooftop considering roof slope and sunlight criteria.

**Table 4.** Estimating the number of buildings and increase in green area considering roof slope and sunlight criteria.

| | | | **Area (m$^2$)** | **Buildings (Number)** | **Increase in Green Area (%)** |
|---|---|---|---|---|---|
| Vegetation at Ground level | | | 25,835,522 | n.a. | n.a. |
| Vegetation at Rooftop | Flat Green Roof (≤11°) | Sunny roof (≥3 h) | 1,731,081 | 2890 | 6.7 |
| | | Shaded roof (<3 h) | 453,210 | 1655 | 1.8 |
| | | Shaded-sunny (>0 h) | 2,184,291 | 4545 | 8.5 |
| | Pitched Green Roof ]11°, 20°] | Sunny roof (≥3 h) | 1,095,383 | 2467 | 4.2 |
| | | Shaded roof (<3 h) | 438,954 | 2125 | 1.7 |
| | | Shaded-sunny (>0 h) | 1,534,337 | 4592 | 5.9 |

n.a.: not applicable.

The Flat Green Roof Scenario uses the following criteria for rooftop selection: roof without red tiles, with available area equal or larger than 100 m$^2$, and slope less or equal to 11°. If all solar conditions are selected, i.e., shaded to sunny roofs, 4545 buildings in Lisbon were found suitable for green retrofitting. Those rooftops would represent a green area gain of approximately 2,184,291 m$^2$, i.e., 8.5%.

The Pitched Green Roof Scenario, on the other hand, admits roof slopes between 11° and 20° as possible candidates. In this scenario, if all solar conditions are selected, 4592 buildings were identified, and represent a green area gain of approximately 1,534,337 m$^2$, i.e., 5.9%.

In each scenario, the number of elected buildings represents 35% of the non-tiled roofs existing in the city, and 8% of the total number of buildings in Lisbon.

Based on sunlight availability, sunny rooftops revealed higher potential to become a green urban area. Shaded roofs, on the contrary, have slightly less impact. In fact, shaded roofs in Lisbon generally correspond to garages or small constructions that are adjacent to residential buildings.

If all the rooftops identified in both Flat and Pitched Green Roof scenarios were to be retrofitted into green roofs (9137 buildings), the anticipated increase in the city's green area would be 14.4% (Figure 7). The 9137 buildings represent 70% of all the flat roof buildings, and 14% of all the city's buildings. This value is very encouraging when compared with the situation in Germany, one of the pioneer countries in the promotion of green roof policies. In Germany, 14% of all the flat buildings already benefit from this technology [49]. The potential green roofs identified in both scenarios could have a beneficial impact on individual building energy conservation, but also a direct cooling effect in the local climate. Both effects contribute to minimize the heat island effect.

Note that this methodology does not take into account the presence of artefacts, such as roof overhangs, small chimneys, dormers, or antennas. To be integrated into this analysis, such identification would require more detailed 3D data, i.e., a DSM with a sub-metric resolution, obtained from a point cloud with higher density (more than four points/m$^2$) and a derived DSM with higher resolution. However, the choice of a higher density point cloud increases data costs and data volume, which also demands for more sophisticated processing algorithms. Furthermore, when mapping local capabilities one may consider that the space occupied by those roof elements is not large, and thus represents a small contribution to the available roof free area [50].

In Figure 7, the spatial distribution of potential green roofs in the city, according to the Flat and Pitched Green Roof Shaded to Sunny scenario, can be visualized. It is clear that the northern part of the city has higher potential than the southern part. This is explained by the city's expansion in the late century. The historical centre and old neighbourhoods are located in the south-eastern part of the city. These areas are characterized by red-tiled roofs, identified as not suitable for retrofitting in this initial analysis. In the northern part of the city there are the more recent urbanizations, where red-tile and concrete roofs co-exist.

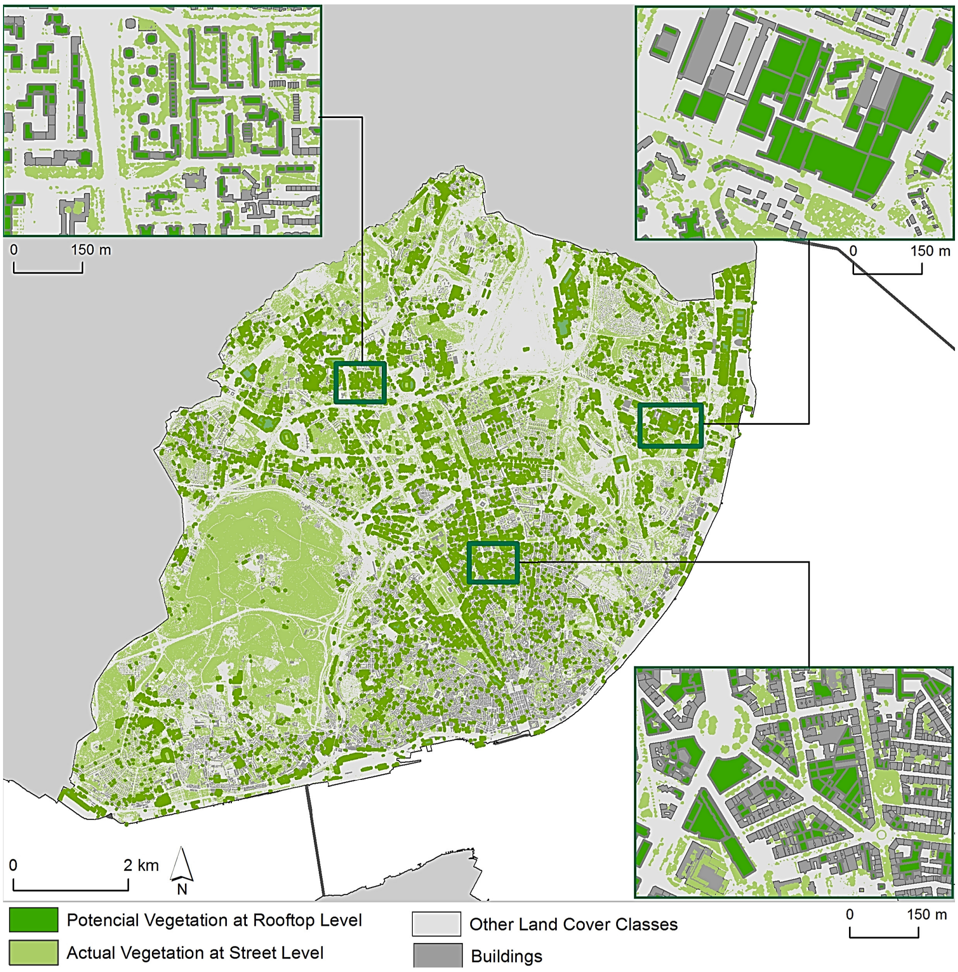


**Figure 7.** Current vegetation cover at ground level and potential vegetation at rooftops considering the Flat and Pitched Green Roof and Shaded to Sunny scenario.

## 5. Conclusions

Promoting green infrastructure is a priority objective for the European Union [51], generally achievable through policy initiatives. One way to surpass the lack of green spaces in the built environment is supporting the implementation of green roofs. Nevertheless, information about the local capabilities to receive such infrastructures is an essential decision-making tool that should be made available to city planners and decision-makers.

The proposed methodology is a simple approach that identifies the city's potential to receive green roofs. The results constitute a detailed geographical database allowing urban planners and city decision-makers to obtain accurate assessments and decide based on realistic sustainable goals [31]. Remote sensing technologies have proven to be an efficient source of information about the built environment. In fact, remote sensing data can be used not only to assess potential locations but also to monitor policy implementation.

The conclusions of this study fall into two general categories: (i) the relevance of GIS-based tools to support the decision-making process; and (ii) the efficiency of the proposed methodology to quantify the city's green area.

The first main idea concerns the relevance of GIS in informing decision-making processes. Increasing green urban areas is a central decision in the "sustainable cities" paradigm. The big challenge is to incorporate actions within master plans, urban design and strategic action plans, making the goals of sustainable cities achievable. Geographic information technologies are one of the most important elements to monitor the actions of master plans and to follow strategies targeted at sustainable cities. Currently, two topics are of utmost relevance in this context. One of these topics has to do with the comparability between indicators of urban sustainability. In fact, as in the case of green areas, the comparison is more feasible when using land-use and land-cover maps derived from satellite images, since these images guarantee the comparability of surface states of urban elements regardless of their scale. Another topic is related with geographic-based information. Measures of urban sustainability cannot be solely based on indicators obtained from 2D geographical information. 2D information should be complemented by 3D modelling of geographic data [52]. Point clouds obtained from LiDAR sensors or by image matching of Unmanned Aerial Vehicle (UAV) data, allow for such modelling to occur. The major application of 3D point clouds is to generate 3D urban models [53]. These urban models are irreplaceable at the local-scale analysis.

The second line of thought concerns the efficiency of the proposed methodology to quantify the city's green area. Using building rooftops as green urban spaces is a way of promoting sustainable actions in dense urban places, where vacant land is not usually available. According to the municipality, the total number of green roofs in Lisbon (2013) was 12, with 52,085 $m^2$. Until now, the extent of the potential for retrofit had yet to be known. This research presents an estimation of the potential rooftops in the city that are suitable for green covering. According to the implemented methodology, the number of potential green rooftops, in the most conservative scenario, is 4545, with a suitable area of 2,184,291 $m^2$. These findings provide reliable guidance for policymakers regarding the potential number of buildings in the city that would be possible to retrofit. Furthermore, these results can also be used as an architectural design tool for individual buildings. Such findings should influence policy making and provide incentives to target effective sustainability policies regarding existing buildings.

In the present work, an area criterion of 100 $m^2$ was applied in order to segment rooftops. Nevertheless, those rooftop areas that fall below that value can still be researched for the purpose of installing solar panels, which require less area for their implementation (24 $m^2$ according to Santos et al. [31]). Identifying rooftops with geographic capabilities to receive solar panels together with green structures is the next research question we intend to address. From a methodological point of view, future research will include a global sensitivity and uncertainty analyses, in order to assess input factor importance and interaction, regimes, and scaling laws between model input factors and outcomes. Other future developments of the present work should evolve into assessing the impact of green roofs on climate change mitigation and biodiversity conservation in Mediterranean climates. Such information would benefit the identification process described in this research and empower land planners with more realistic scenarios when considering new regulations for already existing buildings (e.g., renovation, rehabilitation, and regeneration) as well as for new ones.

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