

# Solar irradiation changes in the context of rapid urban development

Justyna Jeziorska<sup>1,2</sup>, Helena Mitasova<sup>2</sup>, Anna Petrasova<sup>2</sup> and Vaclav Petras<sup>2</sup>

**Abstract**—Rapid urban development modifies morphology of urbanizing landscapes and influences spatial distribution of solar irradiation, by replacing a complex structure of forest canopy with flat surfaces of building rooftops and parking lots. High resolution analysis of spatial and temporal distribution of solar irradiation is crucial for understanding these changes and their impact on sustainable urban development. This study presents a workflow for modeling solar irradiation based on LiDAR-derived digital surface models (DSMs) using open-source GRASS GIS. The case study was performed on  $1.4 \text{ km}^2$  area within the Centennial Campus of North Carolina State University that was completely transformed from agricultural and forested landscape to built environment over the last 20 years. The 3D models of this area were derived from two LiDAR point clouds acquired in the years 2001 and 2015 and the solar irradiation was modeled for the two days with minimum and maximum direct solar irradiation (winter and summer solstices). As expected, the development of urban areas changes the spatial pattern of solar irradiation increasing the heat in the newly built areas. However, the analysis has also shown that this increase is partially compensated by the decrease in urbanized area where the planted trees have matured mitigating the summer heat.

**Index Terms**—solar irradiation, GRASS GIS, LiDAR, 3D model.

## 1 INTRODUCTION

Aerial expansion of urban areas and rising level of urbanization increasing demand and consumption of energy in urban areas. Hence developing renewable energy solutions is one of the crucial aspects of sustainable development of cities. Among all alternative energy sources available in the context of urban areas, the photovoltaic potential of the cities has gain attention of many research studies in last decades. Approximate estimates of averaged values provided from global and regional solar resource databases [11] are not sufficient for modeling on local scales, since the spatial and temporal variations in solar radiation are modified not only by changing atmospheric conditions. Additionally, the complexity of urban morphology and microclimate adds additional factors influencing the solar potential and causes the local deviations from general trends [3]. Solar energy potential estimation of such complex environments requires not only sophisticated modeling tools but also detailed spatial representation of the surface. In this paper we propose coupling open source solution for solar irradiation modeling within the open source Geographic Information Systems (GIS) framework and detailed spatial representation of terrain obtained by Light Detection and Ranging (LiDAR) aerial survey.

The aim of the study is to assess the change in spatial pattern of solar irradiation of rapidly developing urban area between 2001 and 2015. We hypothesize that the conversion of forested areas to built environment leads to increase in solar irradiation, creating higher photovoltaic energy potential in the area but also increasing the heat island effect.

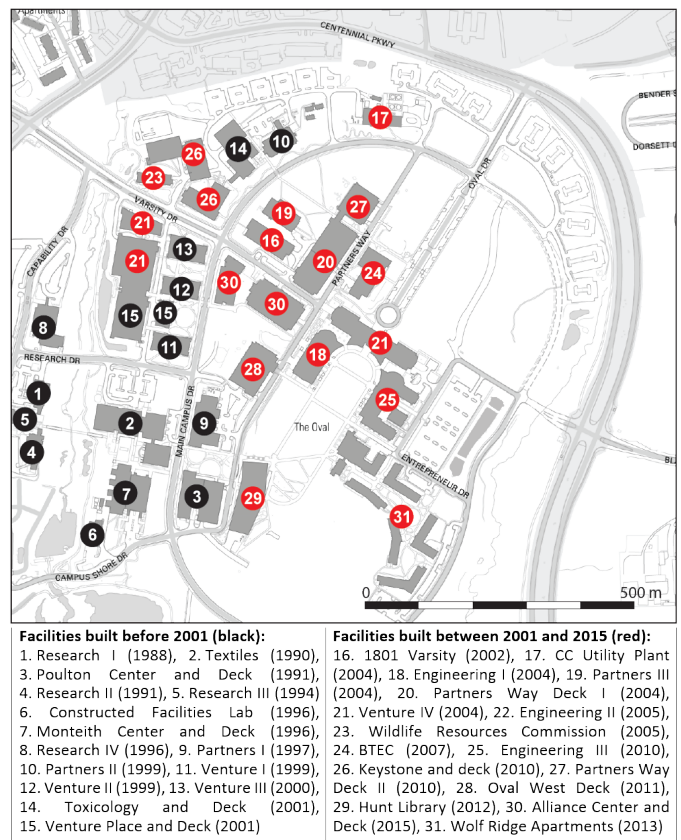


Fig. 1. Study site: Core area of the Centennial Campus, North Carolina State University and its development over the past 28 years (credits NCSU)

<sup>1</sup> Department of Geoinformatics and Cartography, Institute of Geography and Regional Development, University of Wrocław, Poland

<sup>2</sup> Center for Geospatial Analytics, North Carolina State University, USA

## 2 DATA AND STUDY AREA

Research Triangle region located in North Carolina is one of the fastest developing metropolitan areas in the USA. The Triangle is anchored by three universities, the largest of them (with over 34 000 students) [5] is North Carolina State University. To foster research and development collaboration between the industry, government and the university and to provide space for fast growing engineering departments NCSU established Centennial Campus, with the mission to become the premier destination for innovative collaboration between business, research, and education. Although the first building was completed and occupied already in 1989, the fastest growth is associated with the College of Engineering relocation in 2002. Upon completion, Centennial Campus is anticipated to have 840 000 m<sup>2</sup> of constructed space.

The solar irradiation analysis was performed for a 1.4 km<sup>2</sup> (N 39°25.316 73' W 83°27.441 25') core area which has experienced the most extensive transformation from forested to developed land. Between the first available LiDAR data survey in the year 2001 and the most recent one from the year 2015, over 20 facilities were built within this region (Fig. 1). The spatial pattern of changes is documented on orthophotos acquired in the years 1999 and 2013 (Fig. 2). Although there is no orthophoto available for the time of the 2001 LiDAR survey, the LiDAR-based DSM shows that the area didn't change significantly between the 1999 and 2001 and a large forested zone was still located in the center of the study area (see Fig. 2). The trees were almost completely replaced by the built structures, roads, parking lots and lawns by the year 2013 (see Fig. 2). Two datasets of LiDAR data were used for Digital Surface Model generation (see section 3 for processing details). The 2001 and 2015 LiDAR surveys were conducted as part of North Carolina Floodplain Mapping Program. Point densities of the 2001 and 2015 datasets are 0.06 and 3 points per square meter respectively.

## 3 METHODOLOGY

We performed the LiDAR data processing and solar irradiation simulation within the open source GRASS GIS environment [1]. We interpolated the 2001 and 2015 LiDAR datasets with *v.surf.rst* module using regularized spline with tension [?]. Due to the different point densities of the datasets, we interpolated the 2001 data at 2 meter and 2015 data at 1 meter resolution. To create digital surface models we used only the first return points, in case of classified 2015 dataset we excluded points classified as noise and overlap.

The solar irradiation analysis was performed using *r.sun* module implemented in GRASS GIS [1]. The module was developed by Suri and Hofierka [9], [10] and is conceptually based on the methodology developed for the European Solar Radiation Atlas [8]. The spatially and temporally distributed computation estimates beam, diffuse and reflected components of the clear-sky and real-sky global irradiance and irradiation for horizontal or inclined surface locations and produces the result in the form of raster maps [1]. The total daily irradiation ( $Wh/m^2$ ) is a sum of values calculated for a given time-step during the day. Each interval calculation accounts for shadowing and local relief

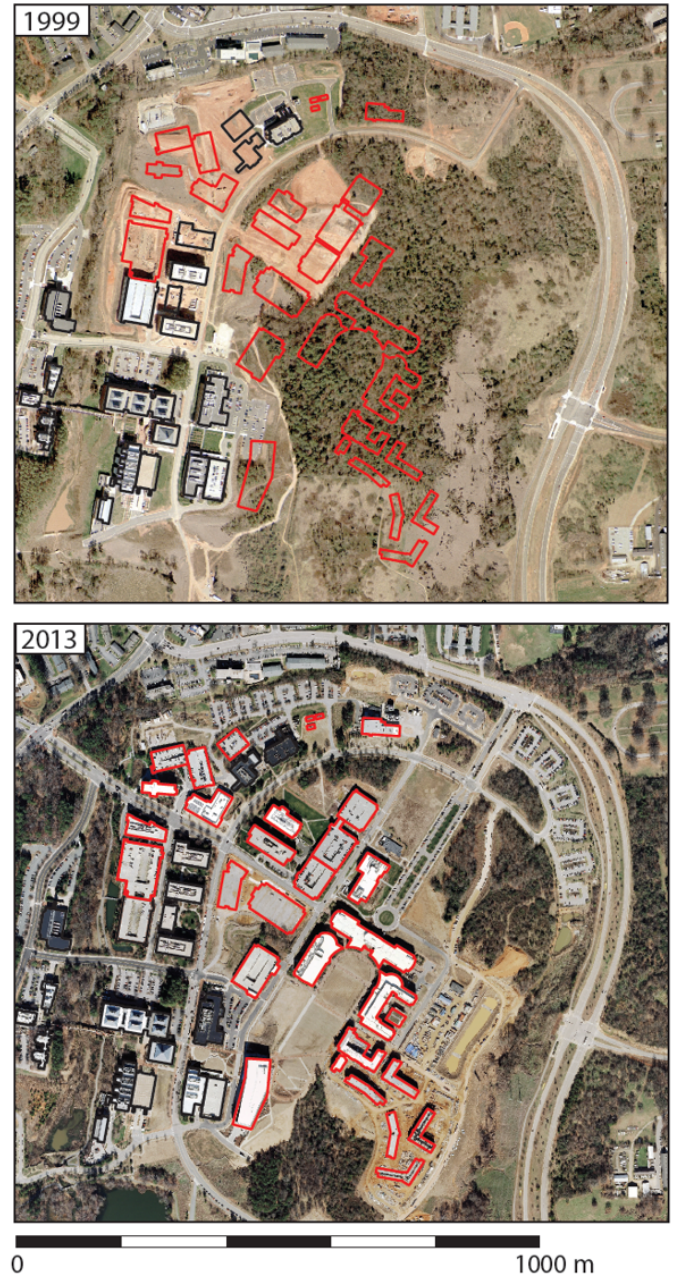


Fig. 2. Study site: Centennial Campus of North Carolina State University. Buildings constructed before 2001 are outlined in black (first LiDAR survey), facilities completed between 2001 and 2015 are outlined in red (second LiDAR survey). Orthophotos source: NC OneMap

based on the input terrain data (DEM or DSM). Other input parameters include Linke atmosphere turbidity factor and ground albedo coefficient which can be spatially variable or constant values. The module can be run in two modes: mode 1 calculates solar irradiance ( $Wh/m^2$ ) and the incidence angle of the solar rays using the given local time; mode 2, used in this study, produces raster-based representation of total solar irradiation ( $Wh/m^2$ ) computed for a specific day. Detailed background and example applications as well as underlying equations used in the module can be found in several papers [9], [10], [7] and [3]. Practical approach and step-by-step guide for running the module in the GRASS



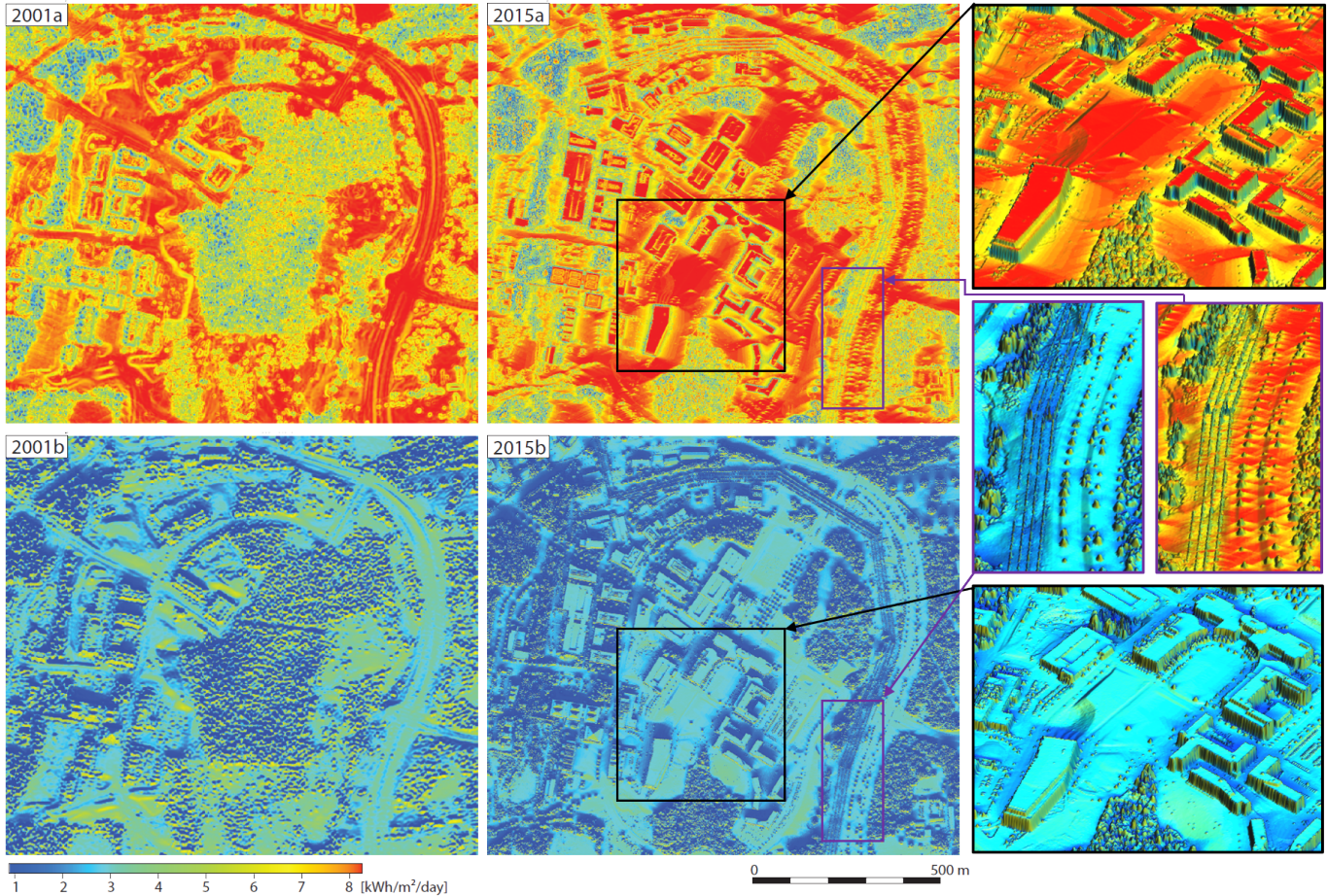


Fig. 3. Modeled irradiation for summer solstice (a) and winter solstice (b). Insets framed in black show seasonal irradiation differences on southern sides of buildings and flat roofs. Purple insets show impact of power lines representation as a surface feature modifying the solar radiation distribution.

GIS is described in r.sun online manual [2] and in the book by Neteler and Mitasova [6].

## 4 RESULTS

Comparison of LiDAR-based digital surface models confirms significant changes in terrain between 2001 and 2015. The most substantial difference is associated with the loss of forested area and the elevation gain within the construction zones, where over 20 facilities were built between the two surveys. The elevation gain was detected also in the southern part and on the edges of the study area, where the trees were preserved and have grown during the 14 years.

Solar irradiation modeling was performed on both datasets for the days of summer and winter solstice (Fig. 3). Constant value of 0.2 was used as an albedo coefficient and Linke turbidity factor was assigned according to the literature value for urban areas [2] as 3.1 for winter and 4.3 for summer solstice accordingly. Time step for calculating the daily sum of the irradiation was set to 0.5 hour. The mean calculated values were higher than the long term monthly regional average acquired from large scale datasets [4] for both summer simulations at  $6.78 \text{ kWh/m}^2/\text{day}$  compared to the  $5.88 \text{ kWh/m}^2/\text{day}$  [4] calculated for the month of June for this geographical zone. The long term regional average for the month of December is  $2.20 \text{ kWh/m}^2/\text{day}$

[4], which is slightly higher than the mean value of the solar irradiation simulated for the day of winter solstice in 2015 as  $2.17 \text{ kWh/m}^2/\text{day}$  and lower than the mean value of  $2.59 \text{ kWh/m}^2/\text{day}$  for the year 2001.

Visual inspection of the irradiation pattern in 2001 and 2015 exposes the most significant rise in irradiation in the central area where the forest present in 2001 was replaced by buildings, roads, parking lots and a large lawn in 2015. The winter solstice simulation results show the overall drop in the irradiation values, especially on the flat rooftops. Comparison of the mean and total values of solar irradiation in the study area confirms the visual observation of decrease in solar radiation for the day of winter solstice. The mean and total values for the day of summer solstice are practically the same and do not reflect the dramatic increase in solar irradiation in the area where the forest was replaced by built environment. In order to explain this discrepancy, the high values of the irradiation (over  $8 \text{ kWh/m}^2/\text{day}$ ) were extracted for the years 2001 and 2015 and their distribution was compared (see Fig. 4). Some of the areas that were hot in 2001 are cooler in 2015, because the trees have grown there, mitigating to some extent the hot island effect, however the newly built areas got hotter because the trees were removed there.

The high resolution simulations also highlight the seasonal

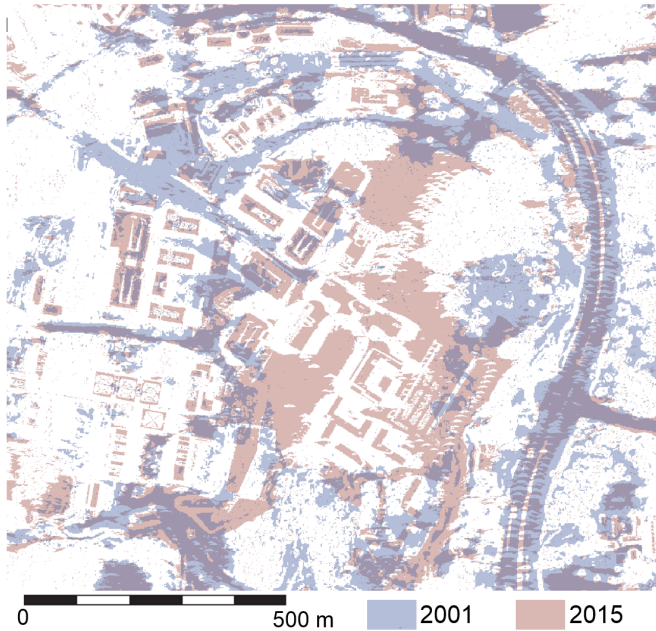


Fig. 4. The spatial pattern of areas with the solar irradiation values over  $8 \text{ kWh/m}^2/\text{day}$  for the day of summer solstice has changed significantly between the years 2001 and 2015

differences in solar irradiation of buildings (see Fig. 3, black insets). In winter, the flat areas such as rooftops exhibit lower irradiation values than the south exposed walls. The distribution is reversed during the summer with much higher irradiation of flat roof areas than the building walls. Although the high resolution LiDAR data allow us to analyze the spatial distribution of solar irradiation at a building level of detail, it can also lead to artificial patterns if the above ground utility features are not filtered out, such as the power lines in the 2015 LiDAR dataset. They are modeled as a surface feature and create an artificial vertical barrier for solar radiation. Hence the artifacts in distribution of solar radiation along the power lines are visible for both (winter and summer) simulations (see Fig. 3, purple insets).

## 5 CONCLUSION

We presented an analysis of change in spatial distribution of solar irradiation due to urbanization performed in open source GRASS GIS. The high resolution maps provided detailed information about the change in irradiation pattern as the forested areas were converted to built environment. The high spatial variability in solar irradiation demonstrates that the spatially averaged values available from regional models are not sufficient for assessing the local conditions and identifying the best locations for photovoltaic energy resources. The analysis has also provided insights into the complex changes in the pattern of solar irradiation. In our study area the hot island effect caused by the new construction was mitigated by growth of the planted or preserved trees. This highlights the importance of urban forest for mitigating the summer heat and the need to manage the preservation of trees in better way during the construction.

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