An automated workflow for informing urban greening based on photosynthetic radiation modelling

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Abstract. The deliberate introduction of vegetation in urban environments, referred to as urban greening, is known to improve outdoor thermal comfort and mitigate the effects of Urban Heat Island in cities. Urban greening can be applied on ground level or elevated parks, rooftops, and building facades. The main parameters that affect plant growth are space, light, water, humidity, oxygen, carbon dioxide, mineral elements, and temperature. Of these parameters, light and temperature are the ones more unlikely to be supplemented in a non-controlled urban setting. This research presents the development of an automated workflow that facilitates design decisions on vegetation growth potential and vegetation species selection within their climatic and geometrical context. This novel scripting-based prototype uses hourly radiation results to extract location specifications, such as photoperiod, hardiness zone, and hourly annual Daily Light Integral values on a user-defined grid. It then seamlessly compares the data against seasonal light and soil temperature requirements of listed cultivars to evaluate their suitability within the constraints of the analysis area. A basic plant dataset is created that is open to expansion based on plants growth data availability. This automated workflow can be employed by agriculturalists, urban planners, and landscape designers to perform vegetation selection for applications such as urban greening in dense contexts or vertical farms.

1. Introduction

The introduction of green infrastructure in urban environments has been presented as an effective strategy to tackle the challenges currently associated to extreme urbanization. Urban greening may take place in different ways, either as public or private green area, as decorative or farming activity, on horizontal or vertical surfaces, on the ground level or rooftops, with tall trees, shrubs, or grass. In either of its forms, it has a positive impact in various aspects of the quality of the urban environment [1]. Besides its aesthetic and social function, urban greening has been proven to reduce air pollution and greenhouse gas emissions, contribute to the biophilic effect that promotes human health and wellbeing [2-5] and mitigate the Urban Heat Island (UHI) effect and its influence on climate change [6-8]. Additionally, it impacts buildings’ energy consumption when acting as shading or applied as a green roof, and enhances storm water management and water quality [9]. With urban farming, it is possible to address food scarcity or urban food distribution inefficiency [10, 11].

Furthermore, on a microclimate level, the presence of vegetation is found to be effective in improving outdoor thermal comfort primarily by reducing the mean radiant temperature $T_{mrt}$ [12]. Based on the US Natural Hazard Statistics [13], heat is the primary cause of death in the US for a 30-year (1990-2019)
or 10-year (2010-2019) average, compared to other weather-related hazards, such as cold, flooding, hurricanes and tornados. Land cover plays a large role in how areas heat throughout the day. Regions that are largely impervious and have dark surfaces, such as many roads and roofs, will heat up quickly and remain hot throughout the day. Green infrastructure provides significant, long-term benefits for heat mitigation. Plants and trees provide shade and moisture and can cool down the air. One of the biggest contributors of climate change and UHI is the creation and retention of heat, which is largely affected by materials’ permeability and reflectivity (albedo), as well as by the existence of shading, parameters that urban greening inherently addresses. In addition, the potential evaporative cooling efficiency from green infrastructure is projected to increase with climate change in most of the urban areas globally except some coastal cities [8].

2. Urban greening feasibility
Several guidelines refer to urban greening as a prominent strategy for mitigating overheating and advancing human wellbeing. Implementing such strategies require a preliminary feasibility study to identify the extent to which such applications are practicable within the specific spatiotemporal constraints of the urban setting. In a high-density urban environment, different urban forms are exposed to different levels of solar radiation due to their shape, orientation, materials’ optical and thermal properties, self-shadowing, and shadowing effects of surrounding objects. Furthermore, solar radiation at a given micro-location also varies due to changes in the sun’s position in the sky and different weather conditions [14].

2.1. Vegetation growth guidelines
The quantity and quality of growth of landscape plants is dependent on interactions between their genetic potential and the above- and below-ground environment in which they are growing. The principal environmental requirements for plant growth include adequate space for root and canopy development, sufficient light, water, humidity, oxygen, carbon dioxide, mineral elements, and temperature suitable for essential physiologic processes [15]. Of these parameters, light and temperature are the two climate-related variables that cannot be easily modified or adjusted in an urban open-air setting, which might be possible within a conservatory setting.

2.2. Plants responses and classifications based on temperature and light
Light has a large impact on plants’ growth, while temperature influences their development. Growth refers to plant size, fresh mass, dry mass, branching and flower number. Development refers to leaves or flowers being developed in the meristematic areas of the plant and temperatures influence how fast leaves and flowers develop. The interaction of temperature and light significantly affects plant quality [16].

2.2.1. Plant Hardiness. According to Raunkiaer [17], temperature is of great importance in the distribution of plants and the entire vegetation of the earth can be divided into following 4 classes: (1) Megatherms (2) Mesotherms (3) Microtherms (4) Hekistotherms. Hardiness refers to a plant's tolerance to winter climatic conditions. Factors that influence hardiness include minimum temperature, recent temperature patterns, water supply, wind and sun exposure, genetic makeup, and carbohydrate reserves. Plants can be classified according to their hardiness or adaptation to local climate. Based on the global plant hardiness zones developed by Magarey et.al. [18], the 2012 U.S. Department of Agriculture (USDA) and the Agricultural Research Service (ARS) developed the Plant Hardiness Zone Map [19] (figure 1). This is the standard by which gardeners and growers in the US can determine which plants are most likely to thrive at a location. The map is based on the average annual minimum winter temperature, divided into 10-degree Fahrenheit zones. It divides the United States into 10 zones with zone 1 being the coldest, and zone 10 being the warmest. Plants’ adaptive ranges may be narrow or broad and they may be placed into one or more of these hardiness zones. The data are available by PRISM Climate Group [20] in spreadsheet format as listings of zip codes, hardiness zone name, temperature
ranges and combination of the last two as zone title for over 40,000 zip-code locations in the United States. Similar data are available for Canada, and hardiness zone maps have been developed as a global database.

2.2.2. Plant recommended DLI and photoperiod. Vegetation growth is dependent on quantity, quality and duration of light, parameters that affect plant morphology, flowering, and plant biomass. Light quantity refers to the intensity or concentration of sunlight, which varies with the seasons and can be measured in cumulative light or light sum or light integral. Quantity of light is measurable in its spectral power distribution. Sunlight supplies the complete range of wavelengths and the photosynthetically active wavelength range of the solar spectrum is 300-700nm.

Photoperiodism is the physiological reaction of organisms to the length of night or a dark period, or, according to Hillman [21], a response to timing of light and darkness. It can also be defined as the developmental responses of plants to the relative lengths of light and dark periods, pointing to the importance of the relative lengths of the light and the dark periods and not the total light energy above a threshold. Based on their flowering response, plants are classified into three categories: short-day plants (long-night) SDP, long-day plants (short-night) LDP, or day-neutral, depending on their response to the duration of light or darkness [22].

Plants can also be categorized into very low light, low light, moderate light, high light, and very high light responses. Based on this classification, a tabulated classification of generalized responses of various greenhouse crops to daily light integrals can be found in [16, 23]. Plants can grow in a wide range of DLI and a deviation of 0.1 mol/d should not disqualify a plant from thriving. Although it is generally accepted that more DLI results in better plant growth, in most cases, there is a “diminishing returns” effect on plant growth as DLI increases [16]. Minimum acceptable quality of plant growth that typically affects the required DLI range derives from commercial production and it doesn’t apply as strictly to urban greening applications. Even in the case of urban cultivation of crops and vegetables within households or small communities, the production scale is significantly smaller, and the demand and requirements can be compromised.

3. Urban greening in microclimate simulations

Several studies have used empirical measurements, simplified simulations and, more recently, detailed simulations to assess vegetation growth potential and provide vegetation selection guidelines. The majority of those are based on empirical data collection using a variation of a quantum PAR meter that measures the Photosynthetically Active Radiation (PAR) expressed as Photosynthetic Photon Flux Density (PPFD), that is ultimately converted to Daily Light Integral (DLI) in mol/m² per day, a metric commonly used to identify recommended levels of light exposure for a plant.

Early attempts to generate contextual PAR simulated maps were incorporated in Ecotect, a software that is currently defunct, which utilized a simplified calculation that derives directly from solar
irradiance. More recently, methodologies [24] and applications [25] are leveraging the overlap between visible wavelength range and photosynthetically active wavelength range of the solar spectrum, and, by utilizing conversion factors based on [26] and [23] they outline a way to simulate PAR and DLI more accurately. This methodology allows the incorporation of context geometries and materials’ properties in a micro-scale level.

4. Automation of informing context-specific plant selection

The developed computational tool automates the process of narrowing down the plants that can grow in a specific area (analysis surface) within a particular geographical region and climate. The automation is realized through a multi-step process that begins with the location report calculating region-specific data such as soil hardiness and monthly average photoperiod. This is followed by the calculation of annual estimates of DLI for the analysis surface. Finally, the calculated values of soil hardiness and DLI are cross-referenced against a database that contains those values for specific plants. This enables the user to evaluate multiple plants and make selections conducive to plants’ growth within the geographical region and area being considered. A schematic outline of this process can be seen in figure 2.

The geographical location data are obtained from Typical Meteorological Year (TMY) weather-data. Longitude and latitude provided in the TMY file are used to determine a zip-code nearest to the site. The zip-code is cross-referenced against the USDA database [20] to derive the hardiness zone and corresponding soil temperature values. The hourly annual values of Global Horizontal Radiation provided in the TMY file are used to estimate the daily photoperiod for the entire year. A non-zero value of Global Horizontal Radiation (Watt-Hours/m²) is assumed to indicate the presence of visible light from the sky.

Hourly annual DLI values are calculated by leveraging the hourly illuminance values generated through an annual daylight simulation. The inputs for the annual daylight simulation are radiation and location data obtained from the TMY file, and the geometry and materials’ properties of the site. Initially, illuminance is converted into Photosynthetically Active Radiation (PAR), expressed as Photosynthetic Photon Flux Density (PPFD) in micromoles per second per square meter (μmol/sec-m²), which is then condensed into DLI expressed as mol/m² per day. Further details of the calculation process can be found in [27].

The feasibility of growing a plant at a location is ascertained through a multi-stage decision process that involves the cross-referencing of different plant DLI range and soil hardiness requirements with the corresponding values for the site (figure 3). The consideration of soil hardiness values in the selection or rejection of a particular plant is optional.

![Schematic outline of the tool development.](image-url)
The calculated hourly annual DLI values that become available for all the analysis surface on a grid, offer flexibility in presenting detailed data on an hourly, monthly average, seasonal average, or annual average basis. Hourly evaluation suggests great potential for detailed analysis. However, it is the designated seasonal ranges that typically permit relevant to plant growth evaluation, using the plants’ growth requirement database. This database can be edited and expanded by the user.

5. Illustrative application in an urban context in Houston TX, USA

The climate of Houston (29.7604° N, 95.3698° W) is classified as humid subtropical climate, with tropical influences. August normally ranks as the warmest month at 94.5 °F (34.7 °C) and January the coldest month at 42.2 °F (5.7 °C). The sun shines for most of the year, and Houston has an annual growing season of nearly 300 days. Houston receives an annual average rainfall of about 50 inches (1270mm). It is a heavily vegetated city, but ground and canopy cover diminish as one approaches the intensely developed city center. The CAPA Strategies Heat Watch report for Harris County in Houston [28], that was developed after Voelkel (2017) and Shandas (2019) [29, 30], reports a close correlation of hotter spots across the city with the absence of vegetation.

The selected study area is in central Houston and comprises a narrow patio that faces east and is heavily obstructed by building elements such as balconies and fences. The analysis grid for calculating DLI is set at 9 inches (15cm) above the ground and the analysis nodes are distanced every 4 inches (10cm) (figure 4a). The analysis grid is extended outside the fenced outline including a less-obstructed patch for comparative reasons. For the purposes of this demonstration, three species that cover a wide range in DLI and hardiness requirements were selected: Adiantum aleuticum, Cyclamen cilicium and Lycopersicon esculentum. Their properties, as seen in figure 4d, were uploaded to the database. Hardiness values, when available, were obtained from [31, 32], photoperiod values were obtained from [33], and DLI ranges from [16].

The location report (figure 4e) indicates a hardiness zone 9a and photoperiod corresponding to mid-to long-day photoperiodism. Figure 4b shows the mapped annual average DLI values ranging from 0 to 14 mol/m² per day, with values reaching up to 18 mol/m² per day at the less obstructed part of the east facing analysis surface.

The colored map in figure 4c illustrates the growth potential of the three tested plants and is accompanied by the detailed plants’ report (figure 4f). Adiantum aleuticum was rejected due to incompatibility of hardiness temperatures. Cyclamen cilicium has potential to grow in the entire area except for the most shaded corners of the patio, and Lycopersicon esculentum has potential to grow only at the most exposed parts of the analysis area.

6. Discussion

Selection of vegetation in an open-air urban setting typically relies on empirical data, familiarity with the location climatic specifics and experience with tested cultivars. The automated workflow presented in the previous chapters can concretely inform the plant selection process. A prototype of the computational tool, tentatively called “PhotoRad” (figure 5), has been developed as a plugin for Rhino-Grasshopper and is effectively accounting for micro-scale geometrical modelling and context materials’ properties. The tool can be customized and can provide a preliminary site evaluation of the growth
potential of selected cultivars. It can be used by anyone interested in employing an informed workflow for vegetation selection.

| Plant Names | DLI$_{min}$ (mol/m$^2$ per day) | DLI$_{max}$ (mol/m$^2$ per day) | Growing season (months) | Hardiness Zones |
|-------------|---------------------------------|---------------------------------|-------------------------|-----------------|
| Adiantum aleaticum | 2 | 10 | 4 5 6 7 8 9 10 11 | 5a 3b 4a 4b 5a 5b 6a 6b 7a 7b 8a 8b |
| Cyclamen ciliatum | 8 | 18 | 9 10 11 | 4a 5b 6a 6b 7a 7b 8a 8b 9a 9b |
| Lycopersicon esculentum | 10 | 30 | 7 8 9 10 11 | 4a 8b 9a 9b 10a 10b 11a 11b |

(e) Location report

Geographical and Soil Data for Houston-Bush_Intercontinental_AF-IX-USA
Latitude: 30.08, Longitude: -95.37
Hardiness-Zone: 9a, T$_{min}$: 28.00, T$_{max}$: 25.00
Avg Photoperiod (Jun to Dec): (11.1, 11.12, 12, 13, 14, 14.1, 13.12, 12, 11.1, 11)
Soil-data matched in Database: Latitude: -95.35, ZipCode: 77032
Average Photoperiod calculated from diffuse radiation data in UPW file

(f) Plants reports

Adiantum aleaticum
Growing season months: April, May, June, July, August, September, October, November
Growing season plant DLI range (min, max): (2.6, 10.0)
Growing season location DLI average: (4.9, 8.9, 11.4)
Plant temperature range (min, max): (40, 20)
The plant temperature range (40, 20) is not compatible with the location temperature range (20, 25)

Cyclamen ciliatum
Growing season months: September, October, November
Growing season plant DLI range (min, max): (4.0, 18.0)
Growing season location DLI average: (3.7, 5.8, 9.3)
Plant temperature range (min, max): (-20, 38)
Site temperature range (min, max): (20, 25)

Lycopersicon esculentum
Growing season months: July, August, September, October, November
Growing season plant DLI range (min, max): (10.0, 30.0)
Growing season location DLI average: (4.6, 6.7, 10.8)
Plant temperature range (min, max): (20, 50)
Site temperature range (min, max): (20, 25)

Figure 4. Study details (a) Input geometry and materials’ properties, (b) Annual average DLI mapped on grid, (c) Plants’ selection maps, (d) Tested plants’ requirements inputs, and (e) Location report and tested plants’ reports.

Figure 5. The tool menu in its primary version as a plugin for Grasshopper: 1) Location data and DLI calculation, 2) Plants’ database and summary data, 3) Plant selection analysis.
6.1. Limitations of the presented study
The authors acknowledge the complexity of the subject and recommend the use of this tool with attention to the quality of the inputs. Effective use of the tool requires some operator expertise relative to performing a typical daylight simulation, as well as basic knowledge of plants’ growth criteria and patterns. The accuracy of the results is then proportionate to the modelling particulars, such as weather file selection, geometry details, materials’ properties, and available vegetation growth criteria. The DLI calculation is subject to limitations that are described in [27] and relate to the TMY weather file selection, the averaged conversion factor for solar radiation, and the greenhouse conditions that typically dictate plants’ DLI requirements. Other limitations are suggested by the lack of dynamic evaluation specifically related to growing plants that tend to cast shadows and affect solar penetration around them in a dynamic and less predictable manner. Finally, the presented workflow is highly dependent on the existence and accuracy of DLI requirements of plants in literature or practice.

7. Conclusion
Urban greening has been proven to be beneficial against several challenges associated with climate change, UHI effect, human health and wellbeing, human thermal comfort, and urban design. Plant selection for urban greening requires knowledge of the multidimensional complexity of plants’ growth, that is typically acquired through empirical data and experience. The present study offers an automated workflow that informs plant selection by leveraging existing hardiness zones databases, solar radiation calculations and state-of-the-art DLI calculations. The climate-related factors that are hard to modify in an urban – as opposed to conservatory – context, are photoperiodism, soil temperatures and solar energy availability. After reviewing the importance of climate related requirements on growth, photosynthetic activity and blooming of plants, the authors developed a customizable computational tool as a plugin for Grasshopper, that can provide a preliminary site evaluation of the growth potential of selected cultivars. Agriculturalists, urban planners, and landscape designers can benefit from this computational method that provides fact-based feedback on plant selection, especially within the restrictions of a dense urban environment. Future initiatives being considered by the authors include validation of the tool using primary research methodologies and field measurements.

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