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A Decision Support System for Plant Optimization in Urban Areas with Diversified Solar Radiation

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Abstract: Sunshine is an important factor which limits the choice of urban plant species, especially in environments with high-density buildings. In practice, plant selection and configuration is a key step of landscape architecture, which has relied on an experience-based qualitative approach. However, the rationality and efficiency of this need to be improved. To maintain the diversity of plant species and to ensure their ecological adaptability (solar radiation) in the context of sustainable development, we developed the Urban Plants Decision Support System (UP-DSS) for assisting plant selection in urban areas with diversified solar radiation. Our methodology mainly consists of the solar radiation model and calibration, the urban plant database, and information retrieval model. The structure of UP-DSS is also presented at the end of the methodology section, which is based on the platform of Geographic Information Systems (GIS) and Microsoft Excel. An application of UP-DSS is demonstrated in a residential area of Wuhan, China. The results show that UP-DSS can provide a very scientific and stable tool for the adaptive planning of shade-tolerant plants and photoperiod-sensitive plants, meanwhile, it also provides a specific plant species and the appropriate types of plant community for user decision-making according to different sunshine radiation conditions and the designer's preferences.

Keywords: Decision Support Systems (DSS); solar radiation; Geographic Information Systems (GIS); urban plants; adaptive planning; plant database

1. Introduction

Urbanization is the most obvious trend in the last 20 years [1]; land use intensity and building density are increasing due to a shortage of land resources. In the context of this trend, soil conditions, air quality, and sunshine environment have undergone drastic changes in metropolitan areas, which have a significant impact on the selection and application of landscape plants [2,3]. Urban plants can provide many ecological benefits and much aesthetic value, and play an important role in improving the environment [4–6], biodiversity conservation [7,8], and promoting public health [9].

However, the survival and healthy growth of urban plants is a precondition of both ecosystem services and human well-being, which are provided by trees, shrubs, and ground cover plants. In general, landscape plants selected for urban greening and urban forestry are 'best performers', which have a strong adaptability to climate, pollution, drought, pests, salinity, insufficient light, and to other adverse ecological factors [2,3,10]. Unfortunately, these perfect plants are hard to find. In addition, the excessive application of a single or a small number of plants will reduce both species diversity and landscape diversity. The proper solution is based on the principle of 'put the right tree in the right place' [11] or 'matching the plant to the site' [12,13]. This strategy can achieve a better balance between the environmental supply and the ecological needs of landscape plants.

According to previous studies, urban plant selection must consider factors such as tolerance to adverse soil conditions, air pollution, extreme climate, and resistance against pests and diseases [12–15]. Each plant has its natural distribution areas; designers can easily select the appropriate plants for greening the region by querying the applied manual of landscape plants, and botany-related sites [16–18]. In addition, these adverse soil conditions can be improved through artificial means [19]. For example, adding sand can increase the permeability of the soil, and lime powder or acid fertilizer can improve the soil pH. Although these methods are likely to increase maintenance costs, the survival of the plants is ensured.

Sunshine is an important ecological factor for plant growth, development and reproduction, and is often overlooked in the microenvironment, which is an important habitat for biodiversity conservation. In practice, empirical-based qualitative approaches, which are often adopted by plant planners [20], are more difficult to put into practice in complex building environments due to limitations' perception of the diversity of the sunshine radiation environment. Once plants are cultivated, the solar condition is difficult to change by artificial means. If the sunshine is inappropriate for the plants, the normal growth of the plants will be affected [21], while the ornamental value of the plant is decreased, or even destroyed. Eventually, it will lead to a great waste of plant materials. Therefore, it is necessary to find an intelligent way to aid the landscape plant selection, and to avoid the shortcomings of the experience-based approach, especially in high-density building areas.

Advances in digital technology make it possible to simulate solar radiation, and its spatial-temporal variation pattern maps are also particularly beneficial in adaptation planning for plant shade-tolerance on an urban scale [22]. In addition, some technologies can also play an important role in determining the geographic location and for assisting the work of urban forestry managers and practitioners [23,24]. An urban plant database may also assist the user in selecting suitable plants by site conditions and user requirements [18]. In general, most of the studies presented above are significant on a regional scale, particularly areas with buildings and terrain that will lead to the diversity of solar radiation. Landscape architects should pay attention to this problem, especially in the process of plant adaptation planning. Combining the sunshine simulation with a digital landscape plant database is a better solution for urban plant selection, thus forming a decision-making support platform for plant planners and designers.

In the early years, Decision Support Systems (DSS) were mainly used in clinical medicine [25], risk management [26], and other related fields [27] to solve complex decision-making problems by providing a structured language, a model library, a database, and an interactive panel. The biggest advantage of DSS is that when faced with decision-making problems, it provides a lot of scientific and rational options through the operation of the model and the retrieval of data information. In the field of landscape architecture, the adaptability planning of landscape plants is also facing a similar problem, that is, how to not only satisfy the aesthetic and security needs of stakeholders, but how also to achieve plant sustainability.

To address the above-mentioned problems, we proposed an Urban Plant Decision Support System (UP-DSS), which may assist landscape planners in plant selection and configuration in the urban areas. In Section 2, we introduce our research methodology, which mainly comprises the solar radiation model and validation, the database design for landscape plants, the logical information retrieval model, and the structural composition of UP-DSS. In Section 3, we demonstrate the practical application of UP-DSS for plant adaptation planning. The main issues are discussed in Section 4. Finally, this paper summarizes the entire research, and explores the direction of future research, in Section 5.

2. Methodology

2.1. Solar Radiation Model

2.1.1. Expression of the Solar Radiation Model

Accumulated temperature is an ecological indicator used to describe the extent of heat abundance in a region. Generally, the number of days over 10 °C is calculated. The accumulated temperature can be used to reveal complex connections between regional adaptability and plant health status in terms of growth, development, and reproduction [28,29]. As is well known, solar radiation is the sole source of both ground and atmospheric heat. This study mainly focuses on the calculation of regional solar radiation, thereby guiding different species of the landscape plant selection and community configuration.

In the comprehensive evaluation model for solar radiation, our research adopted the model of photoelectric potential evaluation, which is commonly used in Europe and Africa [20,30]. The model is expressed as:

$$S_{con} = \int_{1}^{365} \mu(t) A_{sol}(t) S_{int}(t) \mathrm{d}t \quad (1)$$

In Formula (1), S_{con} is comprehensive conditions, μ is solar energy conversion coefficient; A_{sol} is sunshine area; S_{int} is solar intensity, and t is sunshine duration.

For the specific objective of this study, solar radiation can be directly absorbed by plant chlorophyll (a/b) into carbohydrates with the participation of water and carbon dioxide. Therefore, we do not consider the heterogeneity among different plant species, thus μ is equal to 1 and can be eliminated. The formula is simplified as:

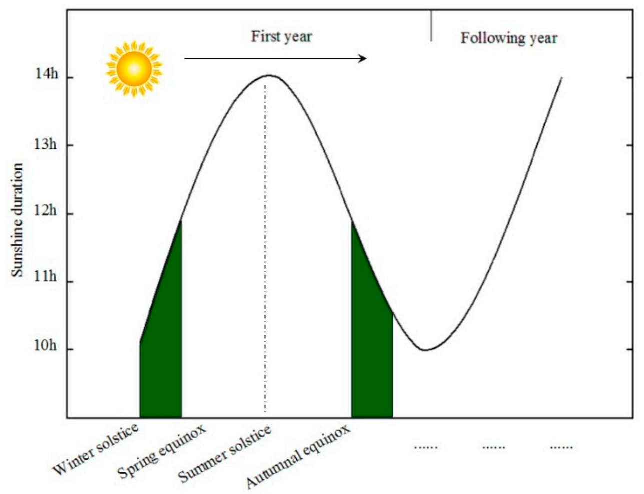
$$S_{con} = \int_{1}^{365} A_{sol}(t) S_{int}(t) \mathrm{d}t \quad (2)$$

Formula (2) is a comprehensive solar radiation evaluation model for this study, which can be combined with historical meteorological data from weather stations to calculate the sunshine total radiation of the target area. In our study, the solar analyst module (ArcGIS packages) was used to calculate the solar radiation through a validated parameter setting.

2.1.2. Sunshine Simulation for Specific Plant Types

Landscape plants have a variety of growth and flowering habits, therefore the solar radiation model should be targeted to describe these differences. For deciduous landscape plants, the demand of sunshine radiation is most important in the spring, summer, and early autumn, but the effect of sunshine radiation in winter is weak. However, solar radiation throughout the year is very important for the growth and development of evergreen plants due to the fact that these have a longer growth period, although their photosynthetic capacity is very weak in winter [31–33]. At the same time, flowering plants also have a more special physiological habit, in particular, these plants are sensitive to photoperiods [34–37].

Therefore, four kinds of solar radiation models were designed to solve these practical problems according to the physiological and ecological characteristics of the landscape plants, combined with digital software simulation features (Figure 1).

<table>
<tr>
<td rowspan="3">Description:
The four plant types are shown in this table, A, B, C, and D, respectively. For flowering plants especially, which are photoperiod sensitive, the solar duration must match their demand, apart from the sunshine intensity, to meet their LCP (light compensation point).</td>
<td>
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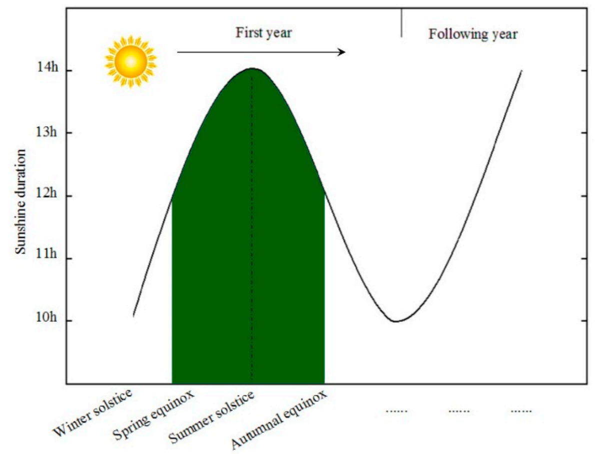
<td>
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<tr>
<td colspan="2">$$S_{dur} = \frac{\sum_{i=1}^{n}(S_{dur.1} + S_{dur.2} + \cdots S_{dur.n})}{N}$$</td>
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<tr>
<td>$S_{dur} < 12$</td>
<td>$S_{dur} \geq 12$</td>
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Figure 1. *Cont*.

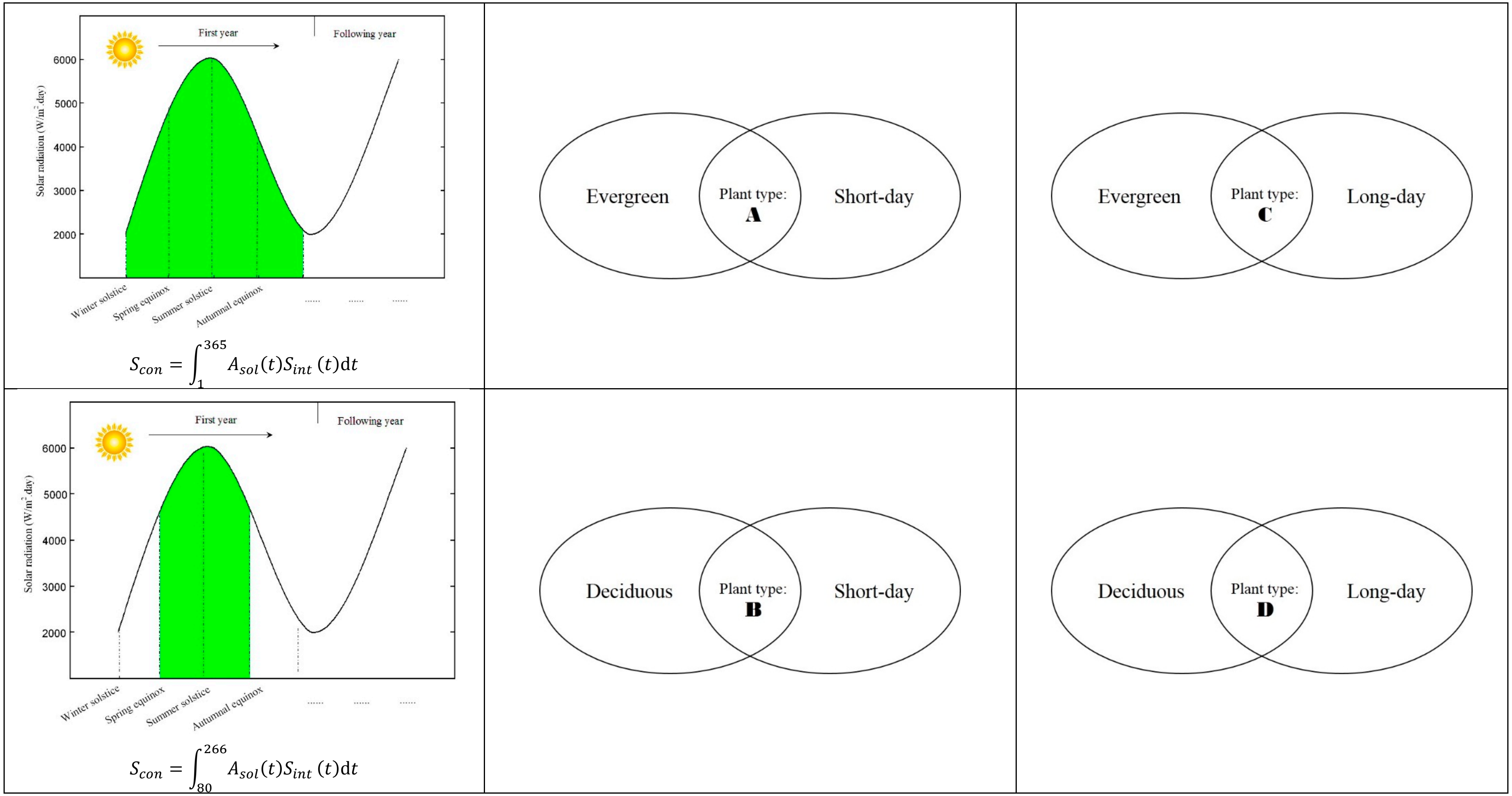

Figure 1. Solar radiation model for the four different plant types.

2.2. Model Calibration

In digital software, the model calibration and parameter settings are critical for practical applications. In this study, we used the Solar Analyst for model testing, which is a tool in ArcToolbox (ArcGIS, Environmental Systems Research Institute, ESRI). The parameter setting item includes the geographic parameters, the data parameters, and the model parameters. Our test focused on two aspects, which are shadow range, and sunshine radiation intensity. These differences exist between digital simulation and real-world testing. Finally, the optimal parameter combination is determined and used as an input to the selection module in the decision support system.

2.2.1. Measurement of Shadow Range

In order to measure the shadow range of buildings that is caused by different solar elevation angles, a test building is selected as a sample for parameter calibration (Figure 2). The boundaries of the building's shadow are measured using surveying equipment (Total Stations in this case), and the time of the survey is also recorded. These allow for calibrating the shadow model.

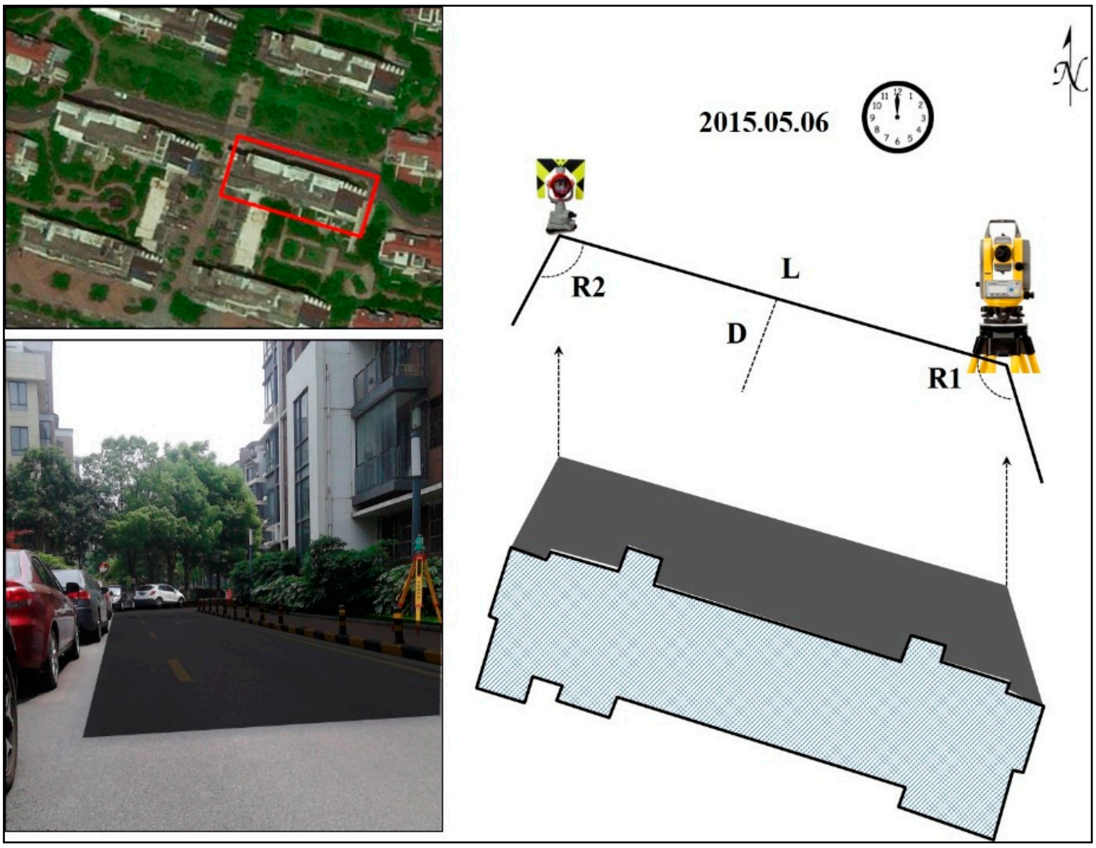

Figure 2. Measurement location and method.

2.2.2. Testing of Solar Radiation Intensity

This test is mainly for the purpose of detecting the simulation degree of our solar radiation model. The test data are used to adjust the scale factor between direct and diffuse radiation for the Solar Analyst. In the test tools, our study adopted the Quantum Meter (Model-QMSS-S) which is produced by Spectrum Technologies, Inc. for the Photosynthetic Photon Flux (PPF) testing of sample test points (Figure 3).

(**a**) (**b**)

Figure 3. Testing locations and method. (**a**) Test instrument; (**b**) test points.

In this test, we selected 30 test points, which were randomly distributed throughout the study area. The sensor head of the Quantum Meter needs to be kept 1 m from the ground and be placed horizontally to reduce errors due to its operation when recording data. It is necessary to quickly mark the number and test time. This instrument is mainly used for the PPF testing, therefore the unit of data is µmoles/m^2/s.

In order to unify the units between the measured data (µmoles/m^2/s) and the simulated data (W/m^2), we performed unit conversions with the following formula.

$$R = R_t \times a \tag{3}$$

where R is the solar radiation intensity, R_t is the PPF value tested by the Quantum Meter, and a is the coefficient of the unit conversion. For sunlight, the a is 0.219, which is from 'Photons to W/m^2'.

2.3. Database Construction of Landscape Plants

2.3.1. Software Platform for Database

The simulation, analysis and evaluation of the solar radiation relates to the spatial location attributes of the study area, and the landscape plant species are retrieved based on the evaluation results. Considering the actual needs of this study, a Geographic Information Systems (GIS) based database is a better choice for the storage of landscape plant information.

In our research, the ArcGIS (ESRI) and MS Excel packages are used to provide the software platform for the landscape plants database. The list of landscape plants, together with their characteristics (attributes), is maintained in MS Excel, and linked to ArcGIS as a table for plant retrieval. Other database software packages may be used in place of MS Excel for better performance if the plant database becomes larger.

2.3.2. Plant Types and Classification

Landscape plant types can be divided according to a variety of methods including different growth habits and morphological characteristics. In the application field, planners and designers are more concerned about the plant morphology, height, deciduous habits, growth cycle and other properties. Common plant types are as follows.

- According to the size and height of the plant body, plants can be divided into trees, shrubs, and herbs;

- According to the plant community structure, plants can be divided into the upper, middle and lower plants;
- According to the appearance characteristics, plants can be divided into bamboos, vines, palm, and aquatic plants;
- According to leaf characteristics and growth habit, plants can be divided into coniferous, broad-leaved, evergreen, and deciduous;
- Herbs, according to the life cycle of the plant, can be divided into annual plants, biennial plants, and perennials.

The classification of plant types is quite complex and less clear depending on the different practical purposes. To support the database construction, plant type divisions and attribution relationships are indicated below (Figure 4).

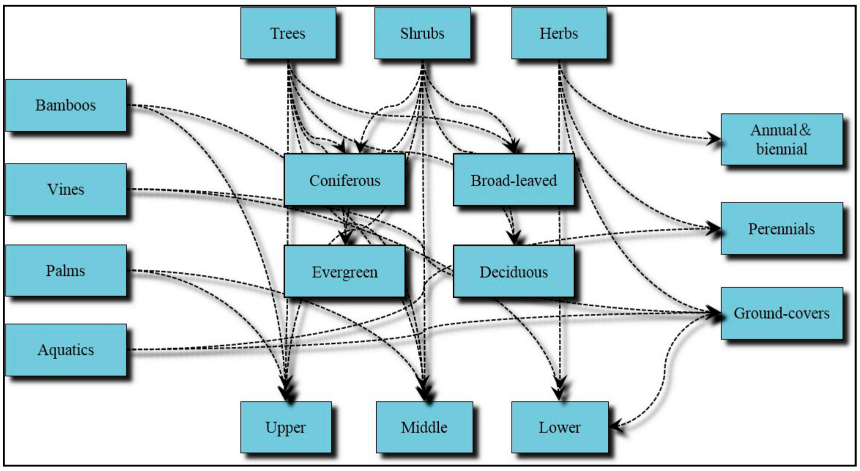

Figure 4. Landscape plant types and classification.

2.3.3. Table Structure

The ecological adaptability of landscape plants for the planting design is a key principle to ensure the healthy growth of plants. The existing plant listings can be used as a reference to the UP-DSS, but the properties of the plants need to be adapted to the structure of the table. The attributes of the table mainly concern basic naming, ecological habits, morphological characteristics, ornamental values, distribution areas, and so on (Table 1).

Table 1. Structure of landscape plant table.

ID	Field	Field Type	Property Description or Value Set
1	CN_name_trade	Text	Chinese name: Trade name. Generic name
2	CN_name_alias	Text	Chinese name: Other names
3	Latin_name	Text	International generic name
4	Family_name	Text	Generic name
5	Genus_name	Text	Generic name
6	Plant_type	Text	{Tree, Shrub, Groundcover}
7	Deciduous_habit	Text	{Evengreen, Deciduous, Annual & biennial, Perennial}
8	Flowering_habit	Text	{Long day, Day-neutral, Short day}
9	Leaf_shape	Text	{Conifer, Broadleaf}
10	Fruit_seed	Boolean	{Yes, No}
11	Sunshine_demand	Text	{Sun-L, Sun-T, Sun-N, Shade-T, Shade-L}
12	Trans_coefficient	Text	Transmission coefficient {$0 \leq T < 0.2$, 0.2, $T < 0.4$, 0.4, T}
13	Allergen	Boolean	{Yes, No}
14	Distribution_area	Text	list of provinces/regions
15	Anti-pollution	Boolean	{Yes, No}
16	Special_smell	Boolean	{Yes, No}
17	Flying_catkins	Boolean	{Yes, No}
18	Ornamental_value	Text	{Leaf, Flower, Fruit, Shape, Trunk}

2.4. Logical Information Retrieval Model

2.4.1. Boolean Model for Plants Retrieval

The landscape plants stored in the database have a variety of attributes, which can serve the practical needs through data retrieval and database management. A better retrieval logic model can simplify the operation of DSS, to facilitate the application of non-technical staff. In this study, we used the Boolean model for plant species retrieval and query.

The Boolean model has many advantages, such as its simple structure and form. The Boolean expression is matched with the data attribute. If the match is successful, it shows as '1'. If unsuccessful, it shows as '0'. The main search algorithms for Boolean searches are 'and', 'or', 'exclusive or' and 'not'. The application of the Boolean model can be combined with Query Builder (ArcGIS) and query functions of MS Excel, to provide richer options of plant types for landscape design.

2.4.2. Steps and Processes for the Plants Retrieval

The realization of decision-making, is based on the set of steps to complete for any DSSs. In this study, the decision-making of landscape plant selection and configuration is also completed through a specific information retrieval step. Both scientific and reasonable information retrieval paths simplify the user's operation, but they can also improve the efficiency of the system. For our research, we have designed three key steps to realize the plant selections and community configurations that are limited by solar radiation for landscape plant adaptive planning in metropolitan areas (Figure 5).

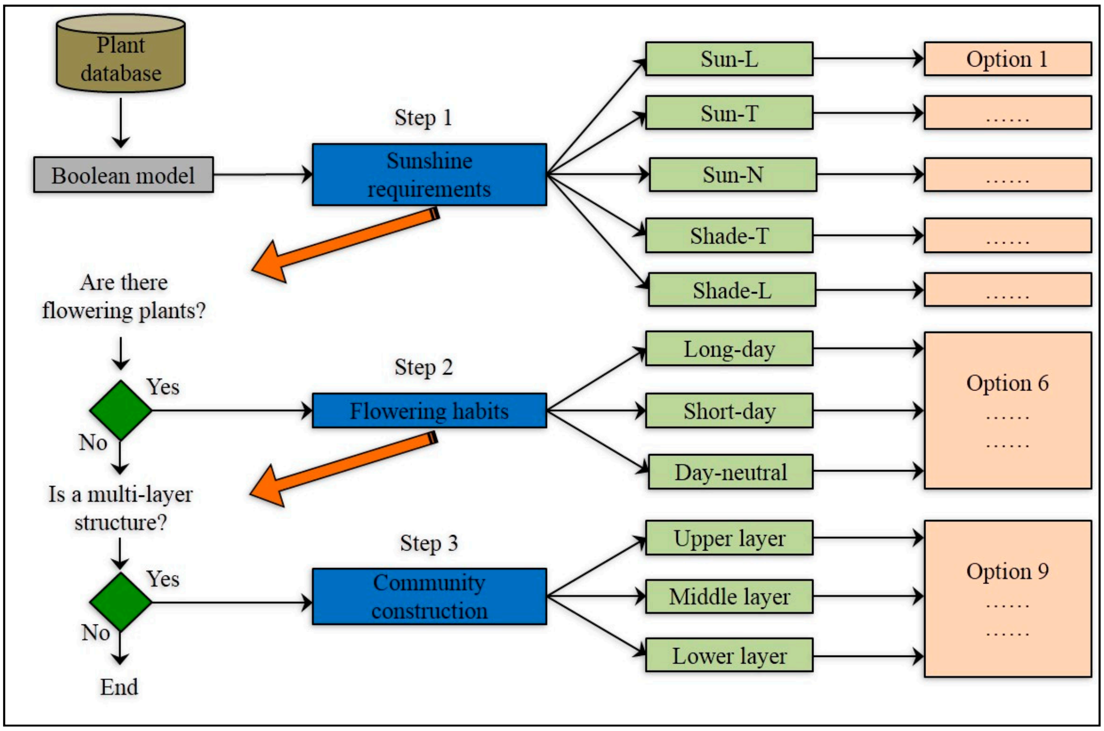

Figure 5. Steps and processes for plants retrieval.

2.5. Structure of UP-DSS

2.5.1. Workflow of UP-DSS

The UP-DSS is a GIS-based platform for the adaptation planning of landscape plants under the restriction of diversified sunshine radiation environments in specific urban areas. It consists of several key parts, which include the database (including building/terrain data and landscape plant data), the model base (the solar radiation model and the logical information retrieval model), and the output of decision-making results. In addition, UP-DSS can be used for urban vegetation conservation; therefore, plant investigation and maintenance is also an important part of UP-DSS (Figure 6).

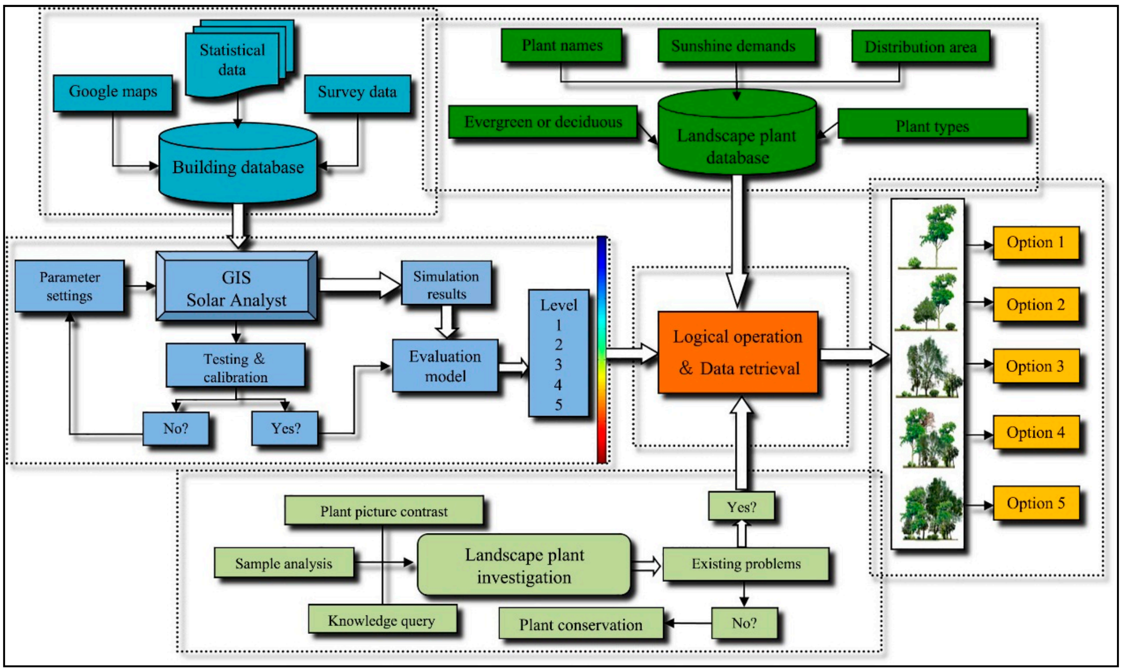

Figure 6. The workflow and technical route of Urban Plants Decision Support System (UP-DSS).

2.5.2. The Modeling Process of UP-DSS Based on Model Builder in GIS

In order to achieve the purpose of the automatic retrieval and matching of landscape plants for 'right tree in the right place', a modeling process is designed using the Model Builder in ArcGIS (Figure 7). The modeling process includes data conversion, model selection, parameter calibration, solar radiation simulation, classification, and information retrieval from the plant database.

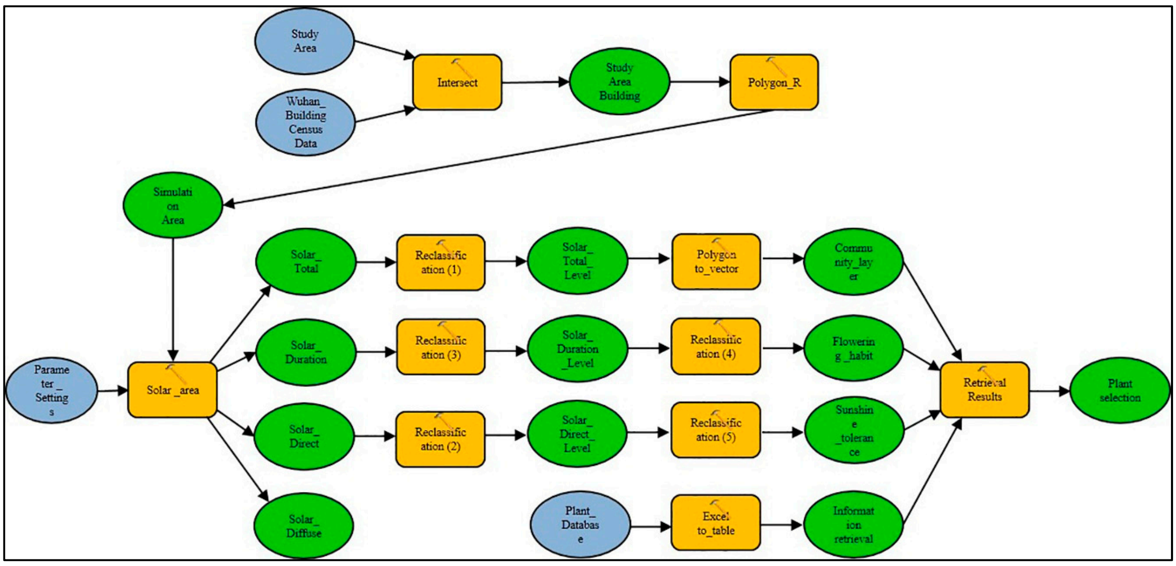

Figure 7. The modeling process and steps of UP-DSS based on Model Builder in ArcGIS (ESRI).

We first determine the scope of the study area by extracting the building information from the Wuhan Building Census data through the clip tool in ArcToolbox, which is converted from vector format to raster format, and which finalizes the building data for the study area. Before the sunshine simulation, we carried out the parameter test and model calibration; these data will be provided in the Supplementary Materials. After determining the optimal parameters of a solar radiation model, the sunshine simulation was run by the Solar Analyst, after which the data conversion and reclassification was completed. Finally, the plant information was retrieved and the whole modeling process was complete.

2.5.3. The Graphical User Interface (GUI) of UP-DSS

In order to allow the user to operate this system, we used the C# language to develop the Graphical User Interface (GUI) of UP-DSS in an ArcEngine 10.0 environment. The GUI has three main operational steps (Figure 8). Firstly, the landscape planner chooses the check items for the ecological functions, ornamental values, and types of plants depending on the practical needs and planning ideas. Secondly, to load the solar radiation pattern of planning areas, which includes the sunshine intensity and sunshine duration, specific values and the area ratio of different levels will be dynamically displayed in the right box. The user can operate the solar radiation map, such as moving, and zooming in and out. On the far right, the annual average values of the total radiation are also shown in 3D form; it provides a more intuitive sunshine feature for landscape planners. Finally, when 'Next' is selected, the interface will run to the results panel, which will display the retrieval results of adaptable plants and communities. If necessary, users can also view real sample images.

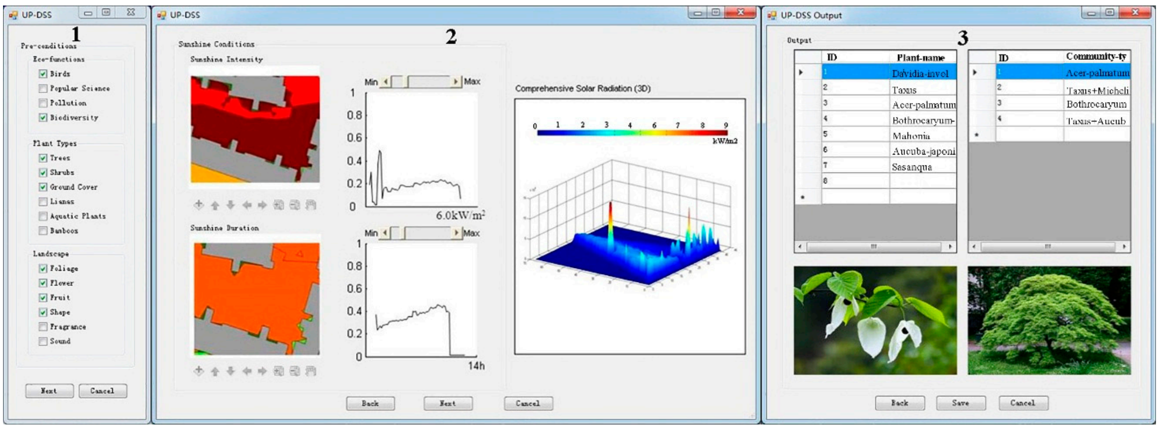

Figure 8. Screenshots of the UP-DSS's Graphical User Interface (GUI).

3. Example of Use and Results

3.1. Study Area and Data

Wuhan is located in the central region of China. The geographical longitude is between 113°41′ E and 115°05′ E, and latitude is between 29°58′ N and 31°22′ N. Wuhan belongs to the northern climate zone of the subtropical monsoon that is characterized by abundant rainfall and sunshine, four distinct seasons, and a hot summer and cold winter. Most subtropical landscape plants can grow healthily in Wuhan. It has been estimated that the number of plant species in the area exceeds 2040 [38].

Our study site is located in the Hongshan District of Wuhan City. The total area is 1.085 km^2, with three residential units, respectively called Da Hua, Jin Di, and Ya Yuan. There are 462 buildings in the study area, and the tallest building is more than 90 m. Building data are provided by local planning departments and supplemented by Google Maps and on-site field investigation. The building data serve as the input of the software platform for the sunshine simulation. At the same time, we also used instruments to locate plants and obtain solar radiation data for model validation and calibration.

In order to make recommendations for landscape plant selection and configuration in this area, we have established a landscape plant database for the region of central China based on the Flora of China website [39]. The database is built with MS-Excel, and then linked to ArcGIS platform.

3.2. Adaptive Planning for the Shade Tolerance of Plants

In the urban built-up area, landscape plant selection and planning for study areas should be based on the specific environmental conditions, which is popularly referred to as 'right tree, right place'. To this end, this section mainly shows the practical application of UP-DSS. However, we only consider the sunshine factor; the simulation and evaluation of other ecological factors, as well as the application of artistic techniques, will be introduced in future research.

As described in the research methodology, according to the parameter input, data loading, and model settings, the UP-DSS automatically generated landscape plant adaptation planning and layout based on the diversity of solar radiation.

The results are mainly divided into five planting areas, which are the Sun-Loving plant area (*Sun-L*), the Sun-Tolerant plant area (*Sun-T*), the Sun-Neutral plant area (*Sun-N*), the Shade-Tolerant plant area (*Shade-T*), and the Shade-Loving plant area (*Shade-L*), respectively (Figure 9). The adaptive planning results of landscape plants needs to be combined with other planning information, such as the road network and other ancillary facilities, in order to ultimately guide this practice.

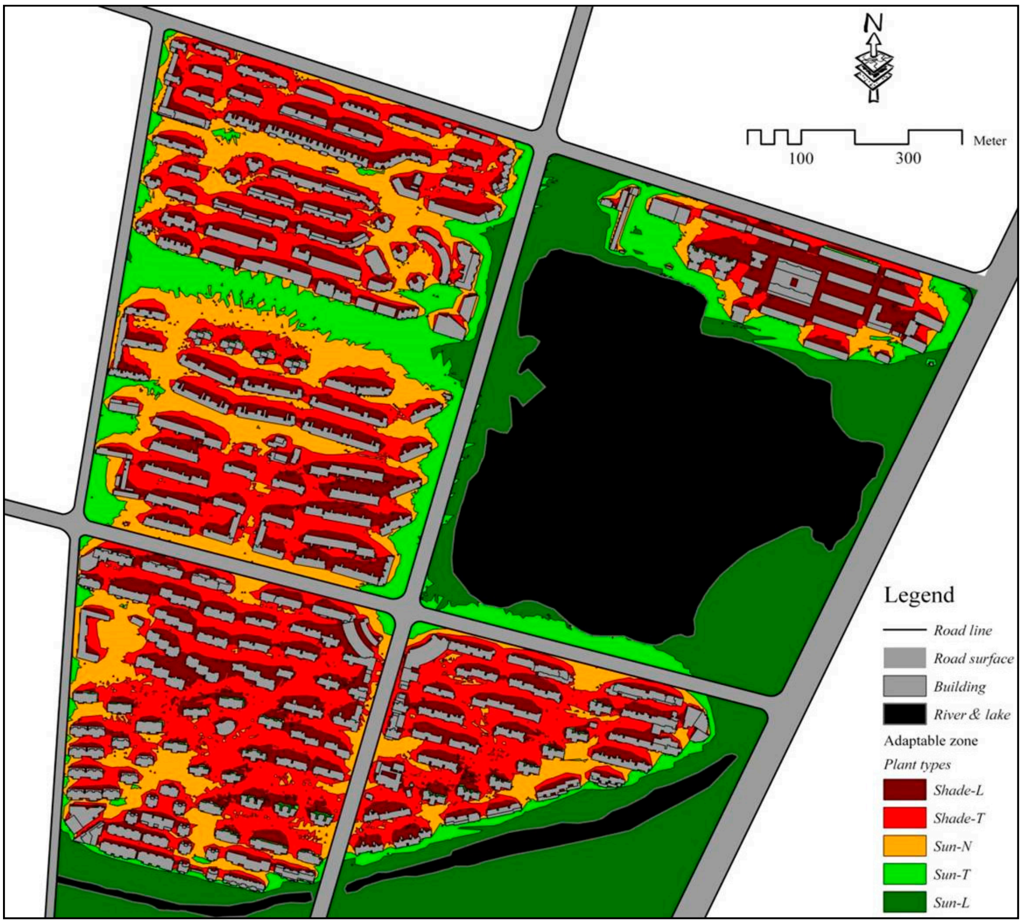

Figure 9. The adaptive planning of landscape plants based on UP-DSS.

3.3. Adaptive Planning for the Flowering Habits of Plants

Landscape plants provide considerable ornamental value, such as leaf shape, trunk morphology, flowers, fruits and so on. Among these features, it is the flowering plants that are most favored by humans. Landscape architects should pay attention to the selection and application of flowering plants. Landscape plants with flowering habits are closely related to sunshine duration, especially for herbs that are sensitive to photoperiod. In order to focus on these photoperiod sensitive plants, the characteristics of sunshine duration were simulated and analyzed for the study area. The adaptive planning of flowering plants was realized by UP-DSS (Figure 10).

The solar duration of the same location varies during the year. In this simulation, the selection and configuration of long-day plants are mainly based on the average value of solar duration in spring and summer. On the other hand, for short-day plants, the average value of solar duration in autumn and winter should be applied. For day-neutral plants that are not sensitive to photoperiod, the application is more flexible, which offers choices in extensive planting areas. Therefore, if a planning area is suitable for long-day plant cultivation then it is also suitable for the growth and flowering of day-neutral plants.

Figure 10. Adaptive planning for photoperiod-sensitive plants.

3.4. Decision-Making for Specific Plant Species

There are large numbers of plant species that can be utilized in urban forestry and urban greening; regional adaptability is the main factor restricting the selection and application of these plants. In this study, a database of plant species was constructed. For retrieving efficiency, the plant species have been tailored to those that can grow in the region of central China.

The retrieval results of the UP-DSS include 103 species of trees, 63 species of shrubs, 66 species of ground-cover plants, and 20 species of climbing plant, bamboo and palm. These are suitable plants for the study area. The detailed quantities are shown in Table 2.

For the purpose of biodiversity conservation, it is necessary to choose as many plant species as possible, as long as these plants can adapt to the ecological and climatic conditions [40,41]. A diversity of plants ensures a rich variety of food types and habitats for more animals, birds, and other creatures in the mixed-dwellers ecosystem.

However, it is also necessary to consider the needs of residents within residential communities. When choosing plant species from the retrieval results of UP-DSS, we should also consider the health and aesthetic appeal for stakeholders. For this purpose, it is important to avoid selecting plants with needles, falling dust, flying catkins, or unusual smells, as well as other allergenic plants. These features of plants can be incorporated into the UP-DSS database; the planner may exclude it through public participation.

Table 2. Retrieval results of landscape plant by UP-DSS.

Community Structure	Plant Types	Shade Tolerance					Flowering Habits	
		Sun-L	*Sun-T*	*Sun-N*	*Shade-T*	*Shade-L*	Short-Day	Long-Day
Upper	Tree	17	62	11	9	4	—	—
Middle	Shrub	4	37	6	9	7	1	—
Lower (Groundcover)	Annual/biennial	9	10	1	2	—	2	4
	Perennial	11	15	9	4	5	1	1
Other	Climbing species	2	4	—	—	2	—	—
	Bamboo species	—	5	1	—	—	—	—
	Palm species	—	4	—	1	1	—	—

Note: '—' indicates no data.

3.5. Decision-Making for the Plant Community

The major issue in the community structure design of landscape plants is to configure the upper tree, middle shrub, and lower groundcover plants [20]. The design method for the landscape plant community is mainly based on the conceptual model, as described in Figure 11. The process is performed under the context of limited solar radiation, assuming no restrictions on other ecological factors. The comprehensive sunshine condition is divided into five grades and 10 sub-grades depending on the solar radiation of the study area. A total of 10 representative plant community types were designed for different sunshine levels (Table 3).

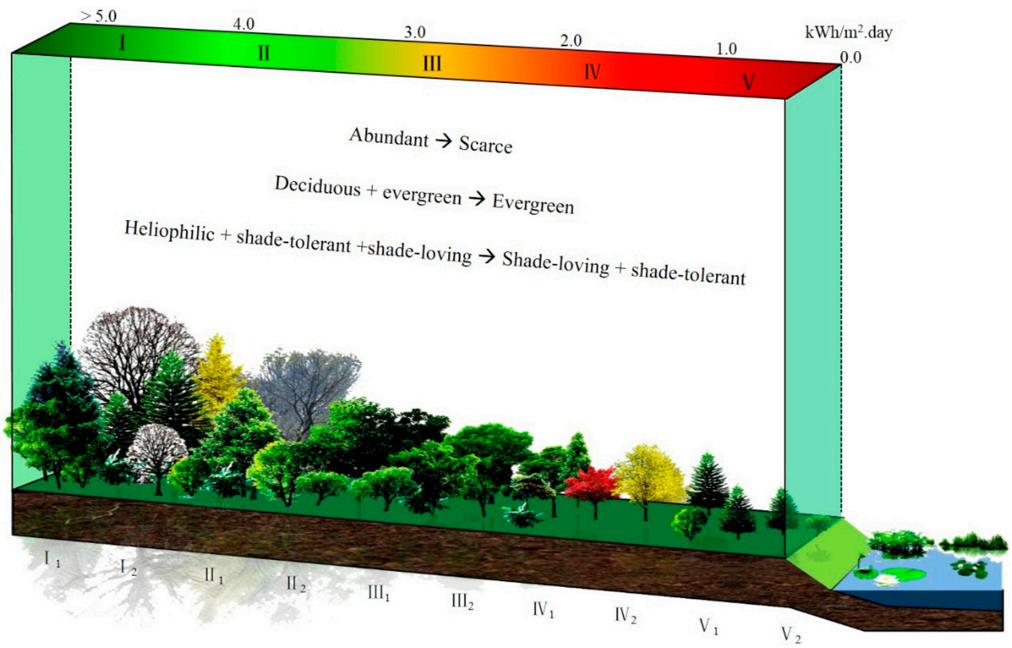

Figure 11. Conceptual model of landscape plant community with limited solar radiation.

Plant communities are composed of the different tree species, shrubs and groundcover species, and any plant species with a relatively stable structure within the hierarchy. We can call this a plant community. In this study, the conceptual model of a landscape plant community was adopted. Combined with the application habit of planners, 100 plant communities have been configured and stored in the final database. These plant communities provide abundant choices for landscape planners, and improve the efficiency of plant selection and configuration.

The community types vary from complex to simple, with sunshine conditions ranging from '*I*' to '*V*'. Only a few plant species grow in areas with poor solar radiation; the community structure here is therefore the simplest. For areas with abundant solar radiation, it is possible to provide a more diversified sunshine radiation environment by configuring different plant layers and densities. The upper plants can provide a shaded microenvironment for shade-tolerant plants and shade-loving plants in areas with abundant sunshine radiation, which depends on the light transmission coefficient of the upper canopy.

Table 3. Design rules of a landscape plant community based on the levels of solar radiation.

Levels	Landscape Plant Community								
	Upper (Trees)			Middle (Shrubs)			Lower (Groundcover Plants)		
	①	②	③	①	②	③	①	②	③
I_1	✹	☻☺	—	✹✷✶✦	☻☺	⭘❍	✹✷✶✦⅄	☻☺	⭘❍
I_2	✹	☻☺	—	✹✷✶✦	☻☺	⭘❍	✹✷✶✦⅄	☻☺	⭘❍
II_1	✷	☻☺	—	✷✶✦	☻☺	⭘❍	✷✶✦⅄	☻☺	⭘❍
II_2	✷	☻☺	—	✷✶✦	☻☺	⭘❍	✷✶✦⅄	☻☺	⭘❍
III_1	✶	☻☺	—	✷✶✦	☻☺	⭘❍	✶✦⅄	☻☺	⭘❍
III_2	✶	☻☺	—	✷✶✦	☻☺	⭘❍	✶✦⅄	☻☺	⭘❍
IV_1	✦	☻☺	—	✦⅄	☻☺	⭘○	✦⅄	☻☺	⭘○
IV_2	✦	☻☺	—	✦⅄	☻☺	⭘○	✦⅄	☻☺	⭘○
V_1	⅄	☻☺	—	⅄	☻☺	○	⅄	☻☺	○
V_2	⅄	☻☺	—	⅄	☻☺	○	⅄	☻☺	○

Note: The symbols '✹', '✷', '✶', '✦' and '⅄' indicates 'sun-loving', 'sun-tolerant', 'sun-neutral', 'shade-tolerant', and 'shade-loving', respectively; The symbols '☻' and '☺' indicates 'evergreen' or 'deciduous'; The symbols '○', '❍' and '⭘' indicates 'short-day', 'day-neutral', and 'long-day', respectively. Label '①', '②', '③' indicates 'sunshine requirements', 'deciduous habits' and 'flowering habits' of landscape plant. The color strip corresponds to the legend of Figure 9.

4. Discussion

4.1. Application of the Solar Radiation Model in UP-DSS

The data acquisition instruments of solar radiation, such as radiometers and sunshine recorders, are usually used in weather station observations of sunshine intensity and sunshine duration [42–44]. However, their application will be very limited in the field of landscape architecture because the debugging and economic costs are inconvenient.

The development and progress of digital technology based on the computer has changed the traditional method of measuring and recording of sunshine radiation. A geometric solar radiation model based on the digital elevation model was developed for agricultural and forestry research [45], which considers the influence of atmospheric conditions, surface orientation, surrounding terrain, etc. The model, as a spatial analysis module has been integrated into a spatial analysis toolbox in ArcGIS, and named the Solar Analyst [46–49]. A GIS-based solar radiation model can also be applied to other areas including photovoltaic assessments [50,51] which provides a new idea for urban thermal environmental assessment [52] and plant adaptation planning for urban greening and urban forestry management [22].

In order to solve the practical problems raised in the previous research, there are four specific models were developed based on the photoelectric potential model combined with the Solar Analyst tool in our research [20,30,46], which provides decision-making for the four common types of landscape plants in the study areas (Figure 1). In fact, the phenology of many plants, such as deciduous leaves, is often influenced by other ecological factors and is not strictly seasonal in different regions. Therefore, we also need more extensive records and statistics on the phenology of various landscape plants in order to facilitate a more accurate numerical simulation of solar radiation, thereby making decisions for the adaptive planning of shade-tolerant plants.

4.2. The Influence of Other Ecological Factors on Plant Selection

Soil conditions are another important factor affecting plant growth and development by providing nutrients and moisture, but also as a physical substrate for fixed plants. Most studies have found that the physical and chemical properties of soil in urban areas are quite different from that in suburban areas [53,54]. Therefore, this is a scientific approach to urban plant selection through site evaluation of the planting areas [15].

In Wuhan, the investigation and analysis of the urban soil's physical and chemical properties have also provided more research results; the soil pH, organic matter content, N/P/K contents, and the cation exchange capacity (CEC) are all involved [55]. The results showed that the average pH was 7.69, which is higher than the soil's pH in suburbs, while it also has a greater variation range. Other results revealed that the distribution and variation of soil nutrients are more irregular. Researchers believe that the main reason for this phenomenon is fertilization and conservation.

In addition, the plant growth space, pests, and other stress factors should also be considered in the future development of UP-DSS for urban plant adaptation planning, although these factors are weakened or eliminated at present by artificial measures. Our research can also incorporate some analysis modules into UP-DSS, which can be used to simulate the spatial distribution of soil properties when combined with sampling and testing [56,57], as well as simulating plant growth rates over time or adding the canopy and height information to the database at different age stages of urban trees and shrubs [58].

4.3. Expansion and Improvement of Plants Database

The landscape plant database is a core component of UP-DSS. In this study, we have set up nearly 20 kinds of plant properties for systematic information retrieval and logical operations. Most of the selected landscape plants are native species which have been widely distributed in the central China, or some exotic plant species which have proven to be well adapted to local climatic conditions. In order to eliminate the regional restrictions of UP-DSS, and to provide a platform of plant shade-tolerant planning for a wider range of regional applications, we will also extend the database in the next stage of the study to meet such practical needs.

Shade tolerance is a key feature of landscape plants, which shows the traits for maximizing photosynthetic carbon gain in low light versus those minimizing losses [59]. These gene-based physiological traits are difficult to change, but the morphological characteristics of plants will change in order to facilitate greater capture of solar radiation in low light conditions [60]. The plant tolerance for shade is mostly tested in the laboratory environment by means of related equipment [61–63], such as Li-6400XT, for the photosynthetic efficiency test of herbs and small shrubs (seedlings). However, there is still a lack of extensive test data on sunshine requirements (e.g., the light compensation point) of the landscape plants in metropolitan environments, especially for the larger shrubs and trees.

5. Conclusions and Future Research

Landscape plant selection and configuration are an important aspect of landscape planning and design in practice [64]. For landscape plants, the concept of adaptability has been recognized by landscape architects, planners, and horticulturists. Factors of regional climate, soil conditions, sunlight, and pollution have been discussed in studies of plant adaptability [3,65–68]. However, these studies were mainly focused on qualitative methods. Quantitative modeling and evaluation based on digital technologies is rarely applied, especially from the viewpoint of solar conditions. The purpose of this study is to present a sound strategy and tool, and use it to select the suitable landscape plants for greening areas with limited and diversified solar radiation.

We introduced a prototype decision support system for urban plant configuration (UP-DSS). The system is set up on GIS platform, which is composed of the landscape plant database, the information retrieval model, the solar radiation model, and the graphic user interface. UP-DSS may help to meet the objective of 'right tree, right place' by providing a reliable operating platform for the selection and configuration of landscape plants, especially within the context of rapid urbanization in the Chinese metropolis.

The low threshold and ease of use are the most important features of any decision support system, and this is the biggest attraction for users. GIS related technology is not yet popular among landscape planners and designers. A stand-alone software package may facilitate the planners and designers in a more efficient way. Given the popularity of mobile terminals (such as smart phones and PC tablets), it is also necessary to develop a DSS based on Android and iOS. For the modeling part, UP-DSS only considers solar radiation in an artificial environment with irrigation and conservation facilities; other ecological factors also need to be incorporated into our future studies.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/9/2/215/s1, Table S1: Field test values of solar radiation, Table S2: The simulation values of solar radiation for test locations based on the Solar Analyst, Table S3: Parameter settings for solar radiation model, Figure S1: Comparison of shadow distance between testing and simulation, Figure S2: Comparison of total solar radiation between testing and modeling.

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