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Green Spaces in Urban Environments: Network Planning of Plant Species Composition

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Abstract: The article deals with the problem of automation and decision-making support in forming sustainable assortments of plant species for landscaped areas of cities, taking into account environmental factors, conditions of growing, properties of plant species, and landscaping practices adopted in the region. The automation of plant species and composition planning for planted territories requires formation of a knowledge base and output algorithms, as well as consideration of specific landscaping practices and techniques adopted in the region. It also requires the application of new modeling methods in combination with methods of spatial analysis, which together with the database of available regional plant species forms a recommendation system and provides decision support in the tasks of landscaping for city planners. The feature of the proposed method based on network analysis is the combination and composition of plant species, as well as the properties of invasive species, which require the use of graph models to form a knowledge base. The proposed method can be useful for forming sustainable assortments of plant species for landscaping squares, boulevards, small courtyards in the city, technical areas and other cases that do not involve the creation of individual complex landscape design. As part of the testing of the proposed method, the authors have formed a unique information base of species. The use of such a database, together with the method of selecting the species composition based on their resistances and interspecies compatibility will ensure the expansion of the diversity of species in the created ecosystem, which will make green areas more resistant to external anthropogenic factors and diseases, as well as preventing the spread of species invasive to the region.

Keywords: landscaping planning; knowledge base; composition; plant species base; recommendation system; decision support; plant species base; network modeling

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1. Introduction

The issue of urban greenery is traditionally relevant for the tasks of forming a comfortable urban environment and ensuring quality of life for citizens [1]. These phenomena become ever more relevant in the context of sustainable cities [2]. Volumetric indicators of the greenness of modern cities are taken into account in such global rankings as the City in Motion Index [3]. There are also a number of ratings dedicated to the direct greening of cities [4]. The amount of required landscaping is regulated by a set of rules, where there are requirements for the necessary green areas in urban planning [5]. All this can serve as proof of the importance of solving the problem of landscaping modern cities in the world.

Green spaces in cities play an important role: they are designed to keep the city from overheating [6] and clean the air from exhaust gases [7,8], and they perform recreational functions, forming a green infrastructure [9,10]. A number of functions of green spaces, describing their contribution to the healthy functioning of the urban ecosystem, are called ecosystem services [11].

In addition to utilitarian functions, green spaces play an important role in the formation of urban identity, creating an emotional connection between people and the city [12]. In large cities, there is an interaction of artificial and natural environments, so it is necessary to balance both sides directing landscape design in the urban structure [13]. In the end, the landscaped areas of the city act as a place where a person living in an urbanized environment can get in touch with the living natural environment, observe its seasonal transformations and correlate them with their own lives. In particular, therefore, the issues of urban greening form one of the main trends of modern urbanism [1,6]. The urban environment is most often aggressive for plants due to changes in the properties and composition of soils, microclimatic changes and factors of external environmental impact. Plants in the urban landscape weaken, becoming vulnerable to attacks of entomophages and phytopathological diseases, which in general affects the green appearance of the city. Moreover, for historical reasons, the species composition of urban greenery for many cities has changed, and includes many invasive species. All these features require careful planning when choosing the species composition of plants for landscaping urban areas. However, species composition planning is not carried out for a large number of landscaped areas due to their small scale. This applies to a lot of small areas, technical planting areas, small squares, barrier planting areas, and other similar areas, which, however, can form up to 80 percent of all the greenery in the city. The situation is exacerbated by the economic factor, which includes the cost of planting, maintenance and removal of plants [14], which for the above green areas are not produced. This leads to the spontaneous landscaping of large—in proportion—areas of the city: sometimes the formation of wasteland, sometimes a natural reduction in the area of green spaces. Thus, the aim of this work is to create a method and technology of decision support for the formation of sustainable combinations of plant species, taking into account the characteristics of their growth and the presence of external influences, as well as the combination of species, to automate the planning of species composition of plants. The method does not take into account the spatial proximity of individual plants to ensure its accessibility across different cities and management systems. Collecting these types of data for all potential green space sites is extremely resource-intensive. To avoid the need to use these data, the method calculates species interactions based on the most radical neighborhood scenario. We expect that the application of the method proposed in the article will reduce the cost of small and not unique or iconic areas to be landscaped. And the resulting assortments of plant species, if planted, will be sustainable and economically profitable for the city, and for the residents, it will allow for the decoration of the urban environment and will make interaction with it more pleasant.

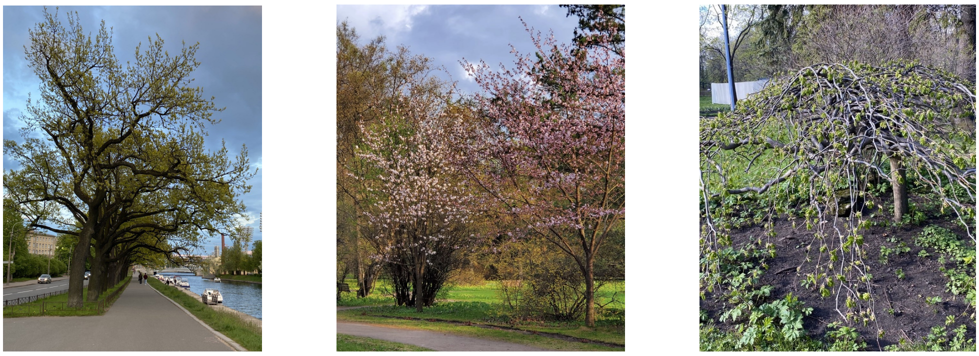
This paper is further organized as follows. Section 2 contains a literature review with existing studies and methods in this and adjacent fields, Section 3 describes the process of plant species composition modeling and Section 4 presents the results of the algorithm application in two locations in Saint Petersburg, Russia.

2. Literature Review

Planning the plant species composition is one of the stages in the overall process of urban greening aimed at creating and controlling the condition and maintenance of urban green spaces. The quality of plant species selection in the planning phase determines the efficiency and cost-effectiveness, and sometimes the feasibility, of all subsequent work in the urban greening process. The units of control in the process of urban greening are green spaces. Green spaces are understood as a set of woody, shrubby and herbaceous plants in a particular area [15]. Each element performs its functions, and together, they form a biosystem, where much depends on their relationship and mutual arrangement.

2.1. The Challenges of Urban Green Spaces

Today's demands on urban green spaces are increasing, and the conditions are becoming more severe, leading to changes in species composition planning processes around the world [16]. The creation of sustainable green spaces involves the use of plant species capable of functioning as designed, even under the stressful conditions of the urbanized environment. Stressful conditions in urban environments are mainly related to anthropogenic influences on plant growth and development; conditions may include general climate change or specific changes in soil salinity in a particular area. Urban green spaces require regular maintenance, the complexity and cost of which are largely determined by the assortment of plants chosen. As a rule, the assortment of urban plantings is divided into three categories: basic, additional and limited-use [17]. Examples of assortments by category are shown in Figure 1. The basic assortment includes trees and shrubs that make up the bulk of urban greenery. They withstand urban conditions well and do not require complex care. They can be used in street plantings and sanitary protection zones, and make up the main green mass on the objects. However, they are usually plants of medium ornamentality, and objects landscaped only with them will be rather monotonous.



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

Figure 1. An example of the formation of green areas based on plants of the basic, additional and limited assortment. (**a**) Row planting of Quercus Robur on Zhdanovskaya Embankment in Saint Petersburg. (**b**) Prunus serrula in the park of the St. Petersburg Forest Technical University. (**c**) Ulmus glabra f. pendula in the Kirov Central Park on Yelagin Island in Saint Petersburg.

Plants of the additional assortment are more ornamental and a little more fastidious than those of the main assortment. Often, these are introduced plants that have shown their resistance in the given environmental conditions. Plants of the limited assortment are difficult to care for, and are extremely demanding to environmental conditions. Trees and shrubs of limited assortment are used on territories protected from loads: inside parks, squares, in intra-quarter landscaping. Their use is justified due to their increased decorative qualities, which give almost unlimited opportunities for gardening. Basically, plants of limited assortment are divided into two categories: introductions and varieties. Sort plants are distinguished by their special decorative properties: a different color of foliage, habitus or shape and color of the flower from the species. Usually, such plants are used to create an accent in a composition. Costs of care and maintenance of green spaces are determined by the presence in the assortment of plants of limited or additional assortment, as well as the need to relocate plants over long distances.

2.2. Factors in the Formation of the Assortment of Plant Species for the City

The process of forming assortments of plants for use in urban areas must take into account many factors, among which the most important are ecological and biological factors, compositional factors and factors of combination of plant species.

One of the factors affecting plant viability is the relationship of plants to atmospheric pollution of PM_{10} and CO_2. Plants are actually absorbing CO_2 and capturing air pollution in the form of PM_{10} making the air cleaner and people healthier. The carbon uptake by different plant species depends on many environmental factors and the health of the plant itself. In urban areas where other depressing factors exist, uptake rates can vary greatly. In the most extensive in vitro study on the subject, 120 native and invasive species were selected for comparison in terms of carbon uptake by leaf laminae [18].

Ecological and biological factors include:

(a) Type of climate and its corresponding temperatures, degree of moisture and prevailing types of air masses [19], which are habitual for the plant species. There are several options for defining climate zones. In addition to geography, the division of countries into regions, for each of which an assortment is defined, is taken into account for the planning of green spaces. In ornamental horticulture is also actively used the system USDA (United States Agriculture Department), where the division into climatic zones is tied to the minimum winter temperature [20].

(b) Soil type. Anthropogenic factors are decisive for soil formation in urban areas. So, despite the fact that each city by its geographical location belongs to a certain climatic zone with a characteristic soil type, there is no possibility of using characteristic trees and shrubs. Urban soils are divided into three groups: natural undisturbed, natural disturbed and artificially created urban soils [21]. Due to the extremely small proportion of undisturbed soils on urban sites, in this research, we will consider artificially created urban soils, evaluated on the following parameters: acidity, fertility and soil type. The main sources of contamination of urban soils are roads, so plants resistant to soil contamination, as well as resistant to overconsolidation formed by constant vibration, are required for planting on adjacent sites.

(c) Relation to light. According to their need for sunlight, plants are divided into conditional groups: heliophytes (light-loving) and sociophytes (shade-tolerant). Between them, sociogeliophytes are distinguished, by which they tolerate partial shading and can withstand untypical light regimes without harm. Lighting requirements may change with plants' age as well as throughout the year. In groups of plants, this determines the distribution of species by tier as well as by light sides [22].

(d) Relation to moisture. Plants can be classified according to their water requirements into the following categories: demanding plants (hygrophytes), which in natural conditions grow in excessively humid soils; moderately demanding (mesophytes), which grow in sufficiently humid places; and low-demanding (xerophytes), which prefer dry areas and can tolerate prolonged drought. According to limiting factors, plants are evaluated as resistant to temporary waterlogging and temporary soil desiccation.

(e) Wind resistance. There are wind-tolerant plants, which are able to grow in open leeward spaces and are moderately resistant; and low-wind-tolerant, which are unable to grow in windy conditions due to the characteristics of the root system and wood.

(f) Dust and gas resistance. Relation to air pollution PM_{10} and greenhouse gasses, e.g., CO_2. Tree and shrub plants are generally divided into three categories in relation to air pollution: resistant, moderately resistant and unstable [23]. For urban sites, depending on the adjacency of roads with different loads, different types are required: at the boundary with the main multi-lane streets is required the use of exceptionally resistant species that are able to function safely and protect less resistant plants. As you move further away from the source of pollution, there is an opportunity to use more vulnerable species.

(g) Disease resistance. Today, in the active international trade in tree and shrub seedlings, many new varieties are being introduced on city streets, but pests or fungal disease spores can also be carried along with them. Pathogens can also persist in the soil and in existing plantings. Disease control primarily requires the avoidance of single-species stands, timely mowing, and the use of "disease-resistant" varieties. Unfortunately, no species is resistant to all diseases, but you can select varieties that are resistant to already identified diseases.

(h) Height of the plant, which can be regulated by both urban planning regulations [5] and the location of plants in the green space, to obtain the required level of insolation.

(i) The diameter of the crown and root system. The size of the root system turns out to be the main limiting factor for the selection of plants in outdoor plantings and a secondary one for gardens and public gardens. Since the soil in the street is seriously compacted due to vibration and pressure, new plantings are actually forced to limit the growth of their root system to the diameter of the planting hole. For this reason, plants with a compact root system and correspondingly compact crowns are recommended for street planting.

Compositional factors include:

(a) Decorativeness. Despite the artistic and compositional value of all plants in the urban environment, they can also be divided into more or less decorative. According to ornamentality, plants can be divided into three main categories: basic—having a green coloring of leaves, as well as flowers and fruits; decorative— having bright coloring of leaves, as well as flowers, fruits, shaped leaves and fragrances; and strongly decorative—combining several features of ornamentality. Depending on the degree of human contact with plantings, plants with different ornamental qualities are used in different plantings. In the garden, basic plants; for the outer perimeter, ornamental for most of the plantings and strongly decorative next to paths and composition nodes; in the square and boulevard, basic and decorative.
(b) Role in urban composition. The main types of organization of tree and shrub vegetation on the site include tree arrays; groups of trees and shrubs; solitary plants (solitaries); alleys; bossets and hedges; elements of vertical landscaping; street plantings; lawns; and flower compositions. In world practice, there are trends towards the use of complexly composed tree and shrub groups on city streets, which allow for the diversification of the urban environment [24].

2.2.1. Factors of Interrelationship and Combination of Plant Species

When forming assortments of plant species for landscaping areas, the presence of related parameters and plant species should be taken into account. Plant species interrelationships can limit the choice of plant species due to the impossibility of planting some species together. Among the most significant factors of plant species interrelationships are the following:

(a) Growing conditions. The basic basis for combining plant species into groups is the identical growing conditions of plants, which are expressed in similar requirements for soil composition, climate, light and moisture [25].
(b) The conditions of the combination of plant species due to the peculiarities of the joint growth of plants, which can be characterized by competition for resources or the successful coexistence of species. For example, certain plants cannot exist close to each other, while others increase their resistance to disease. This phenomenon is called allelopathy [26], a property of some organisms to secrete chemical compounds that inhibit or suppress the development of others. Allelopathy is also sometimes understood as both negative and positive interactions between plants in phytocenoses. Disease of plant species by diseases, viruses and pathogens depends mainly on the state of plant "immunity", but we cannot exclude the factor of epidemics and wave pandemics, the development and spread of which is worth studying, supplementing the matrix of plant species interaction. For example, the spread of Elm borer, which as a pest is not at all dangerous to elm, but as a vector of fungal disease—Dutch elm disease—has destroyed by wave spread the entire middle belt of Russia and is spreading the disease already in Karelia [27].
(c) Features of the accepted practices of landscaping in the region, in accordance with which in the city can be developed precedents for combinations of plant species, well proven in similar conditions.
(d) Compositional features due to the intended function of planting. So, for ornamental purposes, there are stable combinations of species that proved themselves well. It should be noted that the above factors are interdependent, and this should be taken

into account in the planning of plant assortments. For example, ecologo-biological factors are most often related to compositional factors due to the fact that ornamental properties are lower in more hardy plants. In particular, plants adapted to life with low light need less care: moisture evaporates more slowly, and they need fewer nutrients and grow more slowly. They are less likely to have bright, lush colors than light-loving plants.

2.2.2. Factors of Species Invasiveness

Invasiveness of species is a consequence of plant introduction in urban landscaping. There is a classification of invasive plant species according to the status of invasive impact on native vegetation species [28].

(a) Transformers—actively invade natural and semi-natural communities; plants change their appearance and disrupt successional relationships.
(b) Non-native—actively settling and naturalizing in disturbed semi-natural and natural habitats.
(c) Species that disperse and naturalize in disturbed habitats—during further naturalization, some of them may establish themselves in natural and semi-natural plant communities.
(d) Potentially invasive species—capable of regenerating in introduced habitats and have shown themselves to be invasive species in adjacent regions. There are many problem areas where cultivated species are impossible or extremely laborious, and the need and necessity for greening is high. Invasive species can act as a tool to increase the volumetric indicators of greening the territory [29,30].

2.3. Methods for Modeling Plant Species Composition for Green Spaces

Existing approaches to modeling the species composition of plants can be conventionally divided into groups of methods devoted to explaining the existing trends in the formation of plant communities in the areas under study, identifying factors and predicting the dynamics of the state of green spaces. The first group of methods may include works aimed at identifying the factors determining the formation of plant compositions. For example, in a study by Godefroyd [31], it was found that the natural composition of species in green spaces in urban areas is significantly influenced by the type and density of buildings. The authors point out that studies of urban ecology need to identify separate variables for each type of anthropogenic influence without reducing them to a single parameter. Another article identified attributes affecting the distribution of species in Portland parks [32]. Also, based on the analysis of species in parks in Taiwan [33], the authors noted that despite the primary role of landscape architects in the composition of species, artificial landscaping of an urban park will be the basis for the natural processes of its development.

2.4. Network Analysis

This group of methods uses a variety of spatial modeling and data analysis apparatus, the application of which is conditioned by the data and the applied problem to be solved. Ramirez [34] pointed out that network analysis is a suitable tool for studying and describing ecological communities, allowing us to consider factors from the individual level to the level of the entire ecosystem [35]. The method of network analysis is currently widely used in both natural and social sciences [36]. In a study [37], network analysis based on an empirical observation base was also used to determine the neighborhood patterns of different microbial communities in soil. Separately, the application of the null network models of species should be noted as a way to identify the factors affecting their distribution and composition. In particular, in one study [38], an attempt was made to identify cases of symbiotic interaction between fungi and plants based on the predicted neighborhood. In a model defined by environmental characteristics, the probability of species in an area was calculated based on the presence of organic materials in the soil and its acidity. Such models were also used to determine the prevalence of different types of plant species interactions [39]. In this case, the relationships in the graph were directional, which reflected the nature of the interaction (e.g., competitiveness). In addition, network analysis also allows one to display mutually beneficial relationships [40]. In this and other [41] works, the main properties of networks are nestedness, modularity and connectivity. Also, network analysis allows one to trace the influence of abiotic, biotic and interspecific factors on the formation of compositions [42]. In particular, filtering by environmental factors, facilitation of certain species in the presence of their pollinators, and exclusion of species from the composition as a result of competition are named as the three main processes of formation. Boolean networks are used to model such processes [43]. However, when applying network analysis to empirical data, the possible incompleteness of the observed species should be taken into account in order to avoid distortions in the conclusions [44]. A separate direction of the application of graphs in the study of species compositions, as well as in support of decision making on their composition, is knowledge networks. Facts about species and their interrelations are determined by experts and compiled into a network. An example of such a method is presented in Singh's study [45]. Thus, the use of network models to study the vegetation dynamics of green spaces is generally accepted. In our work, we will also follow this approach, applying it to the task of planning plant species assortments for landscaping areas under specified conditions. The solution of this problem will include two parts: modeling plant species, the purpose of which is to form a knowledge base of plant species composition taking into account their growth factors Figure 2; and planning plant species composition for a given territory, the purpose of which is to form stable assortments of species for a specific landscaping area based on the previously formed knowledge base.

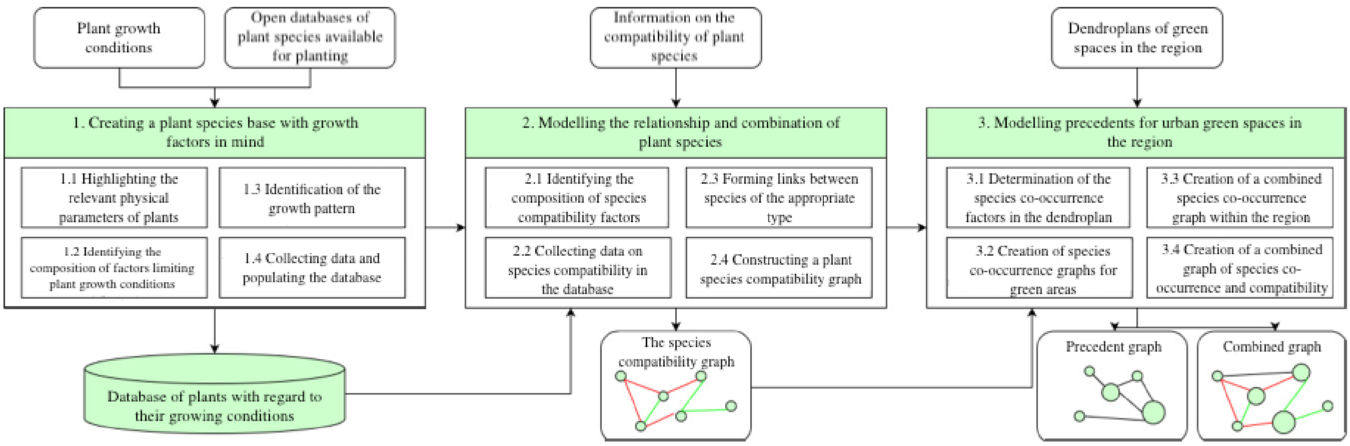


Figure 2. Procedure for modeling plant species composition.

3. Plant Species Composition Modeling

Modeling of plant species composition aims to form a base of plant species, taking into account the conditions and factors of growth, which will serve as an information base in the tasks of planning plant assortments for specific areas to be landscaped. The procedure of plant species composition modeling includes a number of steps illustrated in Figure 2.

3.1. Creating a Base of Plant Species, Taking into Account the Factors of Growth

The first stage involves the creation of a database of plant species, taking into account the conditions of growth and allowing for the formation of an assortment of woody and herbaceous plants for landscaping urban spaces. The authors have allocated four groups of parameters (displayed in Table 1) determining the adaptability of the plant in certain environmental conditions that are the most important parameters for plant growth. 1. Physical parameters of plants, determined to take into account the location of the plant in the spatial structure. They include indicators of the average height of the plant and the average diameter of the crown in the mature state. 2. Limiting factors or environmental parameters that can inhibit certain plant species. The list of limiting factors is formed based on the analysis of the factors mentioned in Section 2.2. By identifying the attitude of plants to each of the parameters, it will be possible to select resistant species to the difficult conditions of the specific territory. 3. Soil parameters. Nutrient composition for the best growth of each plant allows the result to recommend a preferred planting soil when planting in a particular area. Plants respond to soil mechanical composition, acidity and fertility. 4. Parameters of the intensity of spreading, characterizing the ability of species to regenerate and actively reproduce unpretentious life. It is determined to understand the amount of planting material required, survival in areas of possible damage, and forced intentional damage—molding—thereby affecting the ornamental component. It takes into account the aggressiveness of development, the degree of survivability and whether the species is invasive. With the right application, it will allow one to achieve landscaping in adverse conditions.

Table 1. The parameters and characteristics of the plants collected in the database.

Designation	Parameter	Value Range	Description
1. Physical parameters of plants (P)			
P1	Crown size	Meters	Average diameter of the crown of an adult plant
P2	Height	Meters	Average adult plant
2. Limiting factors (F)			
F1	USDA Climate Zone	Number of zone (1–8)	Each zone is defined by temperature readings
F2	Relation to overcompaction of soil	'1'—carries '0'—can tolerate '−1'—does not tolerate	Resistance of plant species to growing in soils subject to compaction due to active movement of people
F3	Relation to soil salinization	'1'—carries '0'—can tolerate '−1'—does not tolerate	Resistance of plant species to growing in soils prone to pollution, excessive salt content near roads treated with chemicals
F4	Relation to soil desiccation	'1'—carries '0'—can tolerate '−1'—does not tolerate	Resistance of plant species to growing in soils whose temporary condition may be waterless and arid
F5	Resistance to waterlogging	'1'—carries '0'—can tolerate '−1'—does not tolerate	Resistance of plant species to growing in soils subject to temporary or spontaneous retention of large quantities of water in their composition
F6	Smoke and gas resistance	'1'—carries '0'—can tolerate '−1'—does not tolerate	The ability of a plant to survive in conditions of maximum air pollution
F7	Wind resistance	'1'—carries '0'—can tolerate '−1'—does not tolerate	Ability to stay in open leeward spaces
F8	Environmental group in relation to moisture	1—xerophytes 2—mesophytes 3—hygrophytes	-

Table 1. *Cont.*

Designation	Parameter	Value Range	Description
3. Soil parameters (S)			
S1	Soil acidity	'1'—prefers '0'—can tolerate '−1'—does not tolerate	Plant's attitude to different acidic compositions of soils: strongly acidic, acidic, weakly acidic, neutral, weakly alkaline, alkaline, strongly alkaline
S2	Soil fertility	'1'—prefers '0'—can tolerate '−1'—does not tolerate	Plant's relationship to soil fertility: fertile, medium fertile, poor
S3	Mechanical composition of soil	'1'—prefers '0'—can tolerate '−1'—does not tolerate	Relation of the plant to the type of soil: sandy, sandy loam, loam, clay, stony, rubbly, heavy, well-drained
4. Propagation intensity parameters (I)			
I1	Aggressiveness of plant growth	'1'—high '0'—medium '−1'—low	How actively the plant is able to spread under normal growing conditions
I2	Vitality	'1'—high '0'—medium '−1'—low	The ability of the plant to recover from pruning, damage, fractures
I3	Invasive	1—is invasive 0—is not	-
5. Parameters of light conditions (L)			
L1	Relation to light	'1'—prefers '0'—can tolerate '−1'—does not tolerate	The ability of the plant to grow in varying degrees of light in places with full light, penumbra, shaded areas.

To illustrate, here is an example of filling the database for four plant species: see Table 2. The selection of these tree species representatives is based on their typical and natural growth with the possibility of forming extensive population communities in the conditions of the study area of the city of St. Petersburg and north-western Russia.

The list of plants is based on the Plantarium Atlas [46]. The Latin names were checked on the World Flora Online website [47]. The main sources for filling the database are the websites of ornamental plant nurseries [48–50]. At present, the database contains 537 plant species, of which 225 are woody plants and 195 shrubs. The database is available at [51]. On the basis of the generated base, it is possible to determine sustainable plant species for given growing conditions, which can be quite extensive for individual areas.

3.2. Modeling Plant Species Interrelationships and Combinations

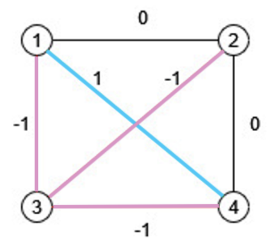
The second step involves taking into account the factors of plant species compatibility in order to then identify sustainable plant assortments.

The interactions of four plant species growing in similar natural–climatic and soil–soil conditions are presented. Approximate distances of the distribution of plant influences on each other, depending on individual plant parameters and environmental conditions, are presented. In modeling the factors of mutual influence of plant species, it should be taken into account that for each pair of plant species, it is possible to determine the value of influence and combinability parameters, which can be of the following types: (a) directed positive impact, characterizing the improvement of the plant properties of the respective species in the zone of influence; (b) a directed negative impact, characterizing the oppression of the plants of the respective species in the zone of influence. Obviously, the modeling needs to take into account the zone of influence parameter for each "active" plant species. The modeling of plant species combinations is non-directional and reflects the availability of good practices of co-locating plants of the respective species for compositional or functional purposes. The modeling of the relationship and combination of plant species is performed by forming a matrix of relationship and combination of plant species, a fragment of which is shown in Figure 3.

Table 2. An example of filling the database.

Parameters	Silver Birch	Norway Maple	European Larch	Domestic Apple Tree
				
Latin name:	*Betula pendula* Roth	*Acer platanoides* L.	*Larix decidua* Mill	*Malus domestica* (Suckow) Borkh
Crown size	7 m	15 m	12 m	3 m
Height	20 m	30 m	25 m	5 m
USDA Climate zone	3	4	3	4
Relation to overcompaction of soil	−1	−1	−1	0
Relation to soil salinization	−1	−1	0	−1
Relation to soil desiccation	1	0	−1	1
Resistance to waterlogging	1	−1	−1	−1
Smoke and gas resistance	−1	1	1	1
Wind resistance	1	1	1	1
Environmental group in relation to moisture	Mesophyte	Mesophyte	Mesophyte	Mesophyte
Soil acidity	Neutral-alkaline soils	Slightly acidic-alkaline soils	Slightly acidic-neutral soils	Neutral soils
Soil fertility	Medium-Fertile	Fertile	Fertile Medium-Fertile	Fertile Medium-Fertile
Mechanical composition of soil	Sandy loam, loamy	Sandy loam, loamy	Sandy loam, loamy	Sandy loam, loamy
Aggressiveness of plant growth	0	1	0	0
Vitality	1	1	−1	1
Invasiveness in northwest Russia	0	0, but has aggressive propagation of plants by seeds	0	0
Relation to light	Full light, half shade	Full light, half shade	Full light	Full light

A model of the relationship and combination of species is a graph in which the vertices are plant species and the edges are the links between the types. For the plant species shown in Figure 4, this graph is as shown in Figure 3. Figure 3 shows that the relationships depend on the characteristics of a particular pair of plant species. For example, the birch has both positive and negative and neutral relationships. Negative relationships may be characteristic of particular plant species, for example, European larch has only negative relationships, which is determined by the peculiarities of the development of particular species. The complete graph for all plant species in the database provided in the PlantCompositionPlanning is shown in Figure 4.



(1) Silver birch and (2) Norway maple: The character of the neighbourhood is neutral. Interspecific competition of active surface root development for: loose nutrient substrate layers, water. Nearby neighbours, up to 10 metres
(1) Silver birch and (3) European larch: Neighbourhood character is negative. Common disease. The rust fungus melampsoridium botulinum kleb. eciostadia develops on the conifers of larch uredostadia and teliostadia on the leaves of birch. Spreading up to 200 m.
(1) Silver birch and (4) Domestic apple tree: The nature of the neighbourhood is positive. The birch tree emits phytoncides abundantly, stimulating the growth and development of the apple tree. If located some distance away from the apple tree and the surface roots do not overlap. Some distance between 20 and 300 metres.
(2) Norway maple and (3) European larch: The character of the neighbourhood is negative. Maple grows faster than conifers and smothers their development. Maple products can have a negative effect on the enzyme intensity of pine and larch. Maple has a strong root system, consumes a lot of water and deprives all the plants in its vicinity of water. Nearby neighbours can grow up to 15 metres away.
(2) Norway maple and (4) Domestic apple tree: The neighbourhood character is neutral. Interspecific competition and predominance of active, fast-growing maple surface roots for: loose nutrient substrate layers and water. Close proximity up to 10 metres.
(3) European larch and (4) Domestic apple tree: The character of the neighbourhood is negative. Larch, during its life activity, releases toxic substances into the soil in the diameter of the crown development to inhibit the active growth of its own seed shoots which can negatively affect the development of the mother plant. These secretions are also toxic and oppressive to other species. Close proximity up to 20 metres.

Figure 3. Fragment of a matrix of relationships and combinations of plant species.

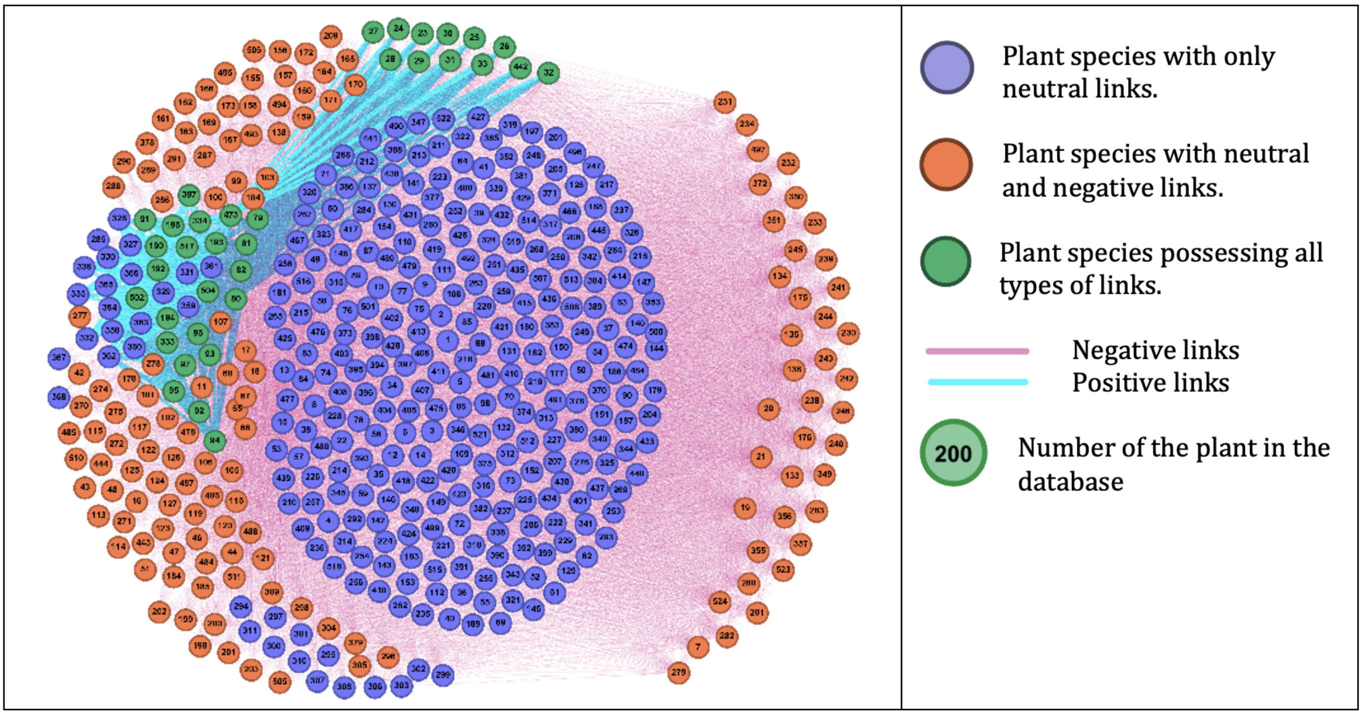


Figure 4. A complete graph of the relationships and combinations of plant species.

Three main groups of plant species can be visually identified in Figure 4: the group on the left of the freestanding species, which have predominantly negative links with other species; the group at the center of the group of plant species with neutral linkages; and the group on the right of the mixed plant species, which includes species with both positive links and negative links, but with proportionally fewer of them compared to neutral links. It can be seen that models of the relationships and combinations of plant species can be quite complex, but it makes it possible to form stable plant assortments for given growing conditions.

3.3. Modeling Urban Greening Precedents in the Region

The third step involves taking into account established or successful landscaping practices in the region under consideration. It is based on an inventory of plant species composition in urban green spaces. The unit of modeling in this stage is greenery located in the territory of urban green spaces (parks, squares, boulevards, flower beds, etc.) and having an established or architect-created assortment of plants. The precedent model involves taking into account one or more possible assortments growing in the park and having different conditions. For example, Figure 5 shows the result of an inventory of plant species within Saltykov-Shchedrin Garden in the Central District of St. Petersburg (coordinates). The total area of the garden is 1.01 ha. Tree cover area is 21.8 m^2; shrubs 259.16 m^2. Group plantings of trees predominate, alternating with open spaces of lawns and group plantings of shrubs. The garden's area is classified according to the USDA frost-resistance zone classification adopted by the international community to determine the possible range of plant growth. The garden's frost-resistance zone corresponds to USDA zone 5.

From the point of view of network modeling, the precedents of coexistence of plant species in parks act as new types of relationships between plant species with the parameters of growing conditions and locations. An illustration of the graph formation for the Saltykov-Shchedrin garden species assortment is shown in Figure 6.

Growing conditions	Trees	Shrubs
1. Climate zone: 5 2. Soil compaction: no 3. Salinisation of soils: yes 4. Soil desiccation: no 5. Waterlogging of soil: no 6. Effects of exhaust gases near roads: yes 7. Effect of winds: no 8. Light characteristic: Lighted area	Rough elm (67) English oak (96) White willow (116) Norway maple (164) Small-leaved linden (504) Siberian larch (200) Common mountain ash (16) Balsamic poplar (327) Ash (368)	Common barberry (20) Thunberg's barberry (21) Tartarian honeysuckle (110) Prickly Pear (133) Cotoneaster (148) Ginnala maple (493) Roseroot (254) Rose 'Scarlet Meidiland' (540) Hungarian lilac (280) Lilac (282) Spiraea vangutta (312) Spiraea ash 'Grefsheim' (315) Japanese Spiraea 'Froebelii' (320) Forsythia medium (342) Cornflower (349) Rose hips wrinkled (356)

Figure 5. An illustration of an account of the range of plants growing in Saltykov-Shchedrin garden in Saint Petersburg, Russia.

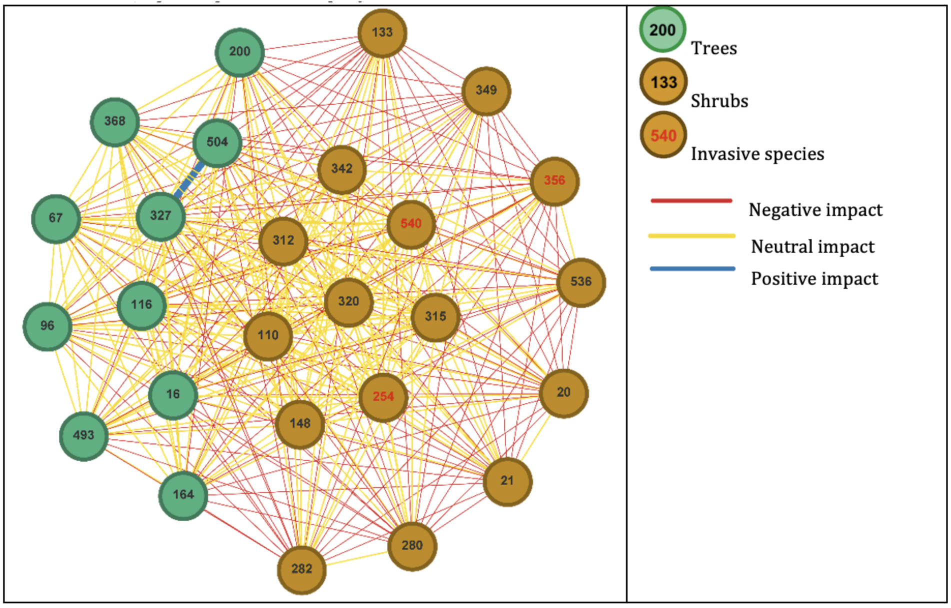


Figure 6. An illustration of the compatibility of the plants growing in Saltykov-Shchedrin garden.

The illustration in Figure 6 makes it clear that on the one hand, invasive species are often found in urban planting due to the nature of urban greening approaches. On the other hand, the reciprocal influence of plants is generally not taken into account, leading to higher maintenance costs for such green spaces. However, the established practices of interdependent planting provide an additional source of data for planning. Figure 7 shows a graph representation of all known precedents for plant species sharing in the database [51] at the time of writing.

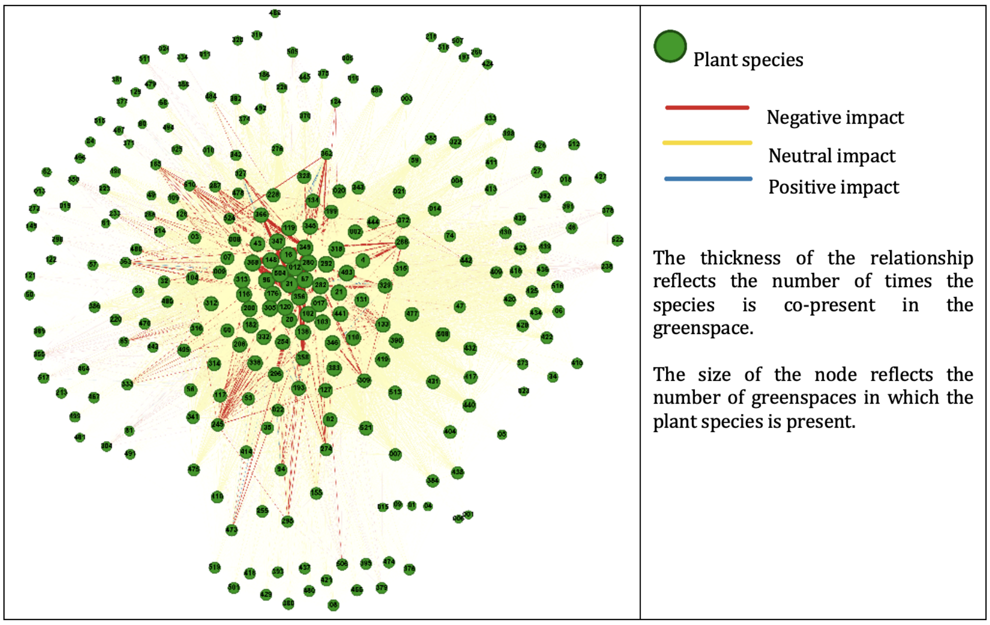


Figure 7. Illustration of a network model of plant species, taking into account co-growth precedents.

Combining the graphs shown in Figures 4 and 7 allows for the formation of a complete model of the relationship between plant species in the city area, taking into account the precedents of use. Figure 8 is an illustration of the complete graph.

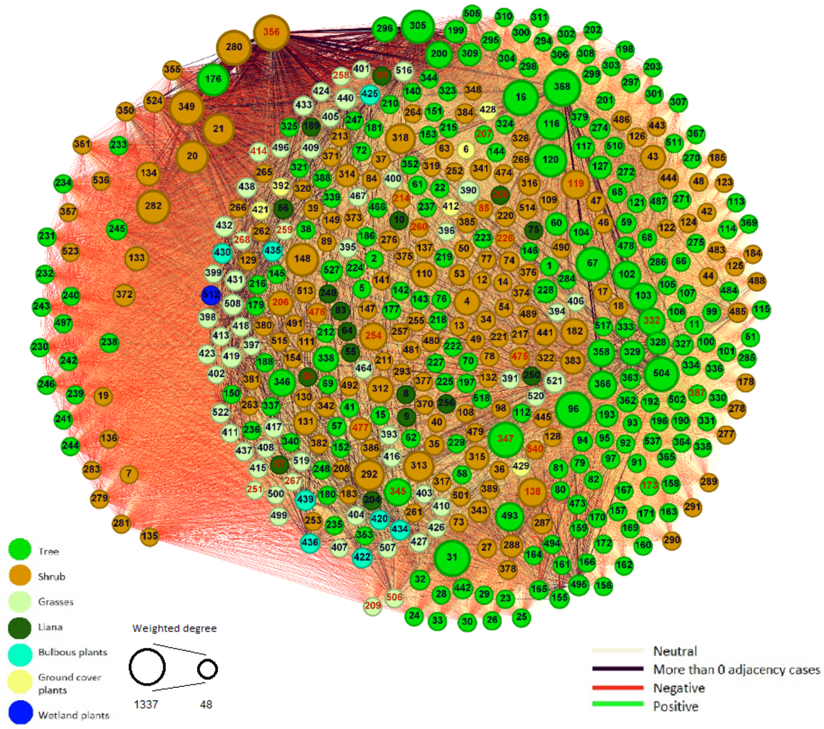


Figure 8. Visualization of plant compatibility. Correlations with plant life forms.

The model generated can be used for plant species composition planning in landscaping tasks when the growing conditions are known [52]. This visualization of the results is presented as a graph. Its vertices are distributed over the plant life forms, as can be seen from the legend on the left. The connections between the nodes are correlated according to the classification shown in the legend on the right.

4. Adaptation of Plant Species Composition Planning

Plant species composition planning is based on a preliminary study of the landscaping area, since it requires information about the growing conditions. The general algorithm for plant species composition planning for a planting area is shown in Figure 9.

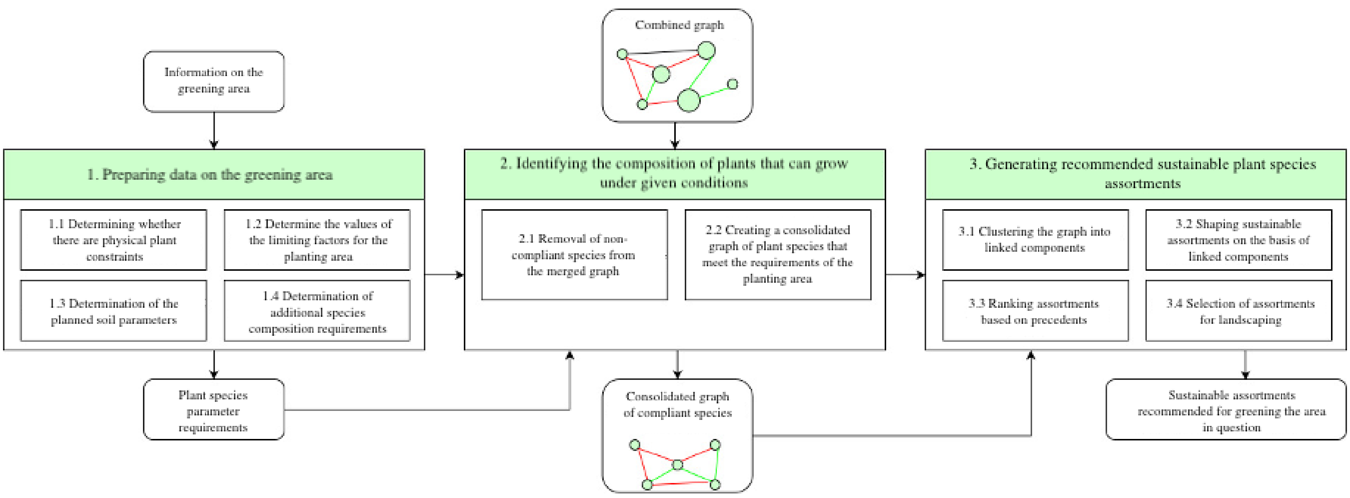


Figure 9. Algorithm for the application of a plant species model for the planning of urban green areas.

The algorithm includes a number of steps. The first is the preparation of baseline data on the growing conditions of the landscaped area.

4.1. Preparing the Data for the Landscaping Area

As an example, we consider the two landscaping areas, the Saltykov-Shchedrin Garden, for which the existing range of plant species is shown in Figure 5; and the Benois Garden in the Kalininsky District of St. Petersburg, for which the existing range is also shown for comparison. For the experiment, we use two versions of the algorithm. The first one updates existing plant composition, adding new possible variants of species, and the second one generates new plant composition. These two versions were used for the Saltykov-Shchedrin Garden and Benois Garden accordingly. Locations of these two areas with their proximity to other large green sites and water bodies are shown in Figure 10.

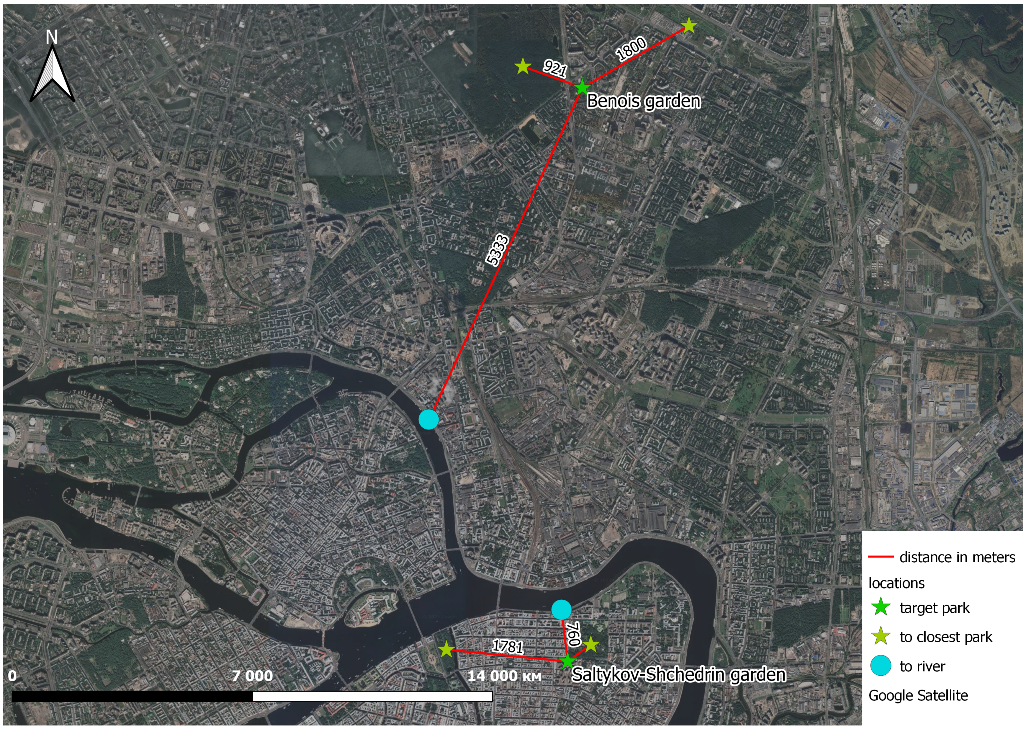


Figure 10. Locations of green areas.

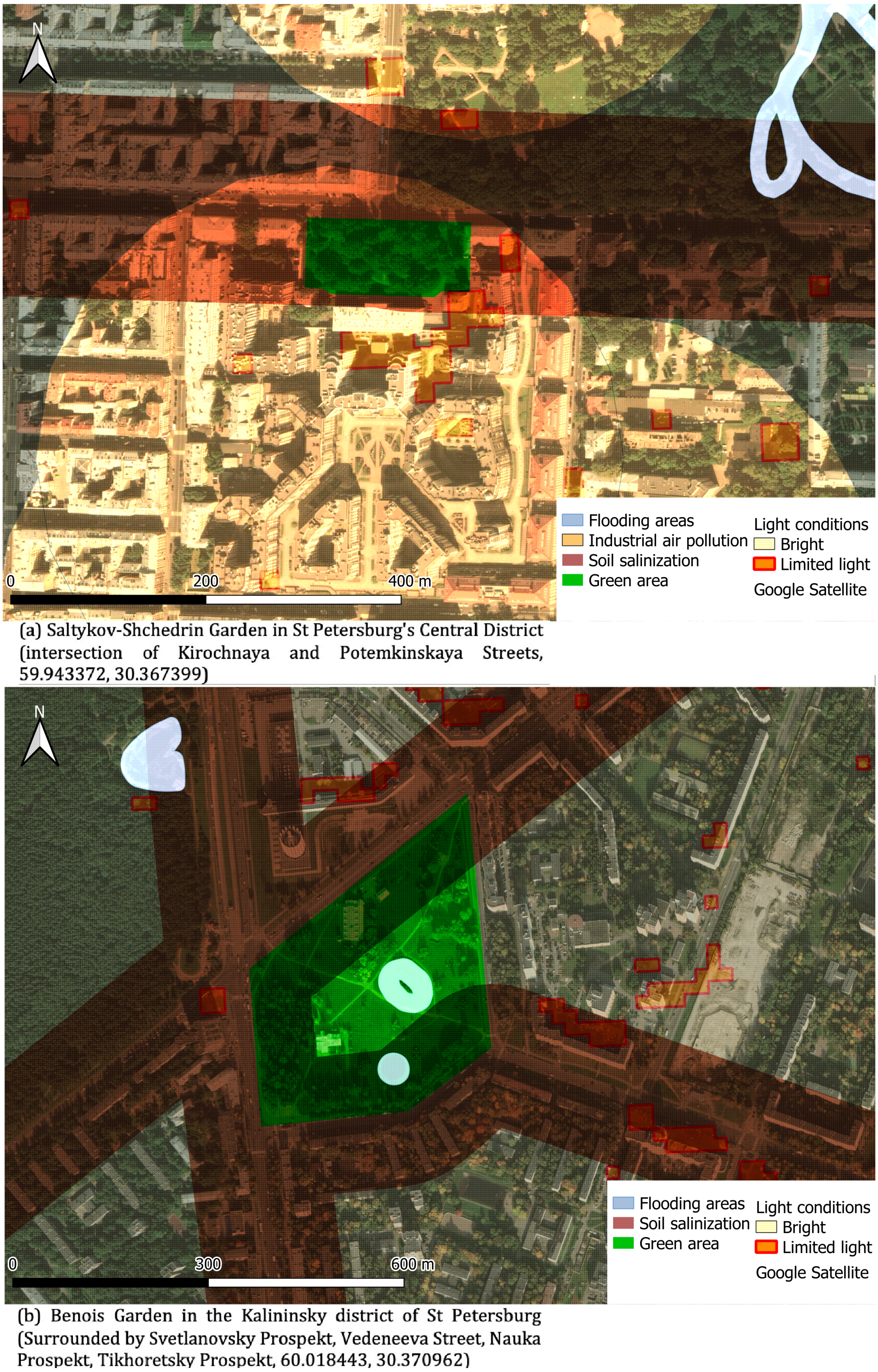
Both zones, which are shown in Figure 11a,b, are classified according to the USDA international classification of climate zones adopted to classify frost-resistant zones according to the boundaries of the range of possible cultivation of plants.

Based on the plant species composition model described in Section 3, the specification of the necessary data is given in Figure 3. The Saltykov-Shchedrin garden has a sufficient number of constraints for plant growth. There is soil salinization and the presence of exhaust gases due to the close proximity to roads. The favorable factors include sufficient lighting, no waterlogging, and at the same time, no soil drying out or compaction. The area is not exposed to winds. Benois Garden has soil salinity, air quality deterioration and wet areas with possible waterlogging, and is subject to soil compaction due to active pedestrian routing. It does not have arid areas and is not exposed to winds. It has adequate light, without significant shading. St. Petersburg is in USDA Climate Zone 5.

4.2. Selecting and Setting Up the Algorithm for Generating the Recommended Sustainable Plant Species Assortments

The second step is to compile a basic list of plant species that can grow under given conditions. The third stage involves creating an assortment of plants for each zone based on their compatibility. Assortments based on the basic set of plant species are formed taking into account the following limitations imposed by the authors:

(a) The number of negative interactions between plant species should be minimal or absent.
(b) The compositions shall include as many combinations of plant species as possible in order to maintain diversity in the emerging system.
(c) The compositions should grow on the same soil types, bearing in mind that urban soils tend to form directly under the planned range of greenery.



(a) Saltykov-Shchedrin Garden in St Petersburg's Central District (intersection of Kirochnaya and Potemkinskaya Streets, 59.943372, 30.367399)

(b) Benois Garden in the Kalininsky district of St Petersburg (Surrounded by Svetlanovsky Prospekt, Vedeneeva Street, Nauka Prospekt, Tikhoretsky Prospekt, 60.018443, 30.370962)

Figure 11. Landscaped areas and vegetation factors.

The task of the third stage of forming plant assortments includes the stage of selecting and tuning the clustering algorithm for the subgraphs obtained in the previous stage, and the stage of evaluating, interpreting and selecting the assortment.

The choice of the algorithm is made subject to constraints (a)–(c). The formation of assortments based on a basic set of plants can be defined as the identification of a set of strongly connected nodes (plant species), while having weaker connections with other nodes than with each other. To date in the field of network analysis, there is a wide variety of methods for defining communities. The two most common approaches are modularity-based optimization [51] and graph partitioning [52]. The first is based on an optimization problem where the degree of overall modularity of the network needs to be increased with a given resolution, resulting in multiple groups of different sizes. The second involves dividing the network into several segments of equal size with a minimum number of edges between them. Both of these methods cannot detect communities below a certain resolution [53], but this disadvantage is not relevant for our study, as the goal is to find the largest community of plant species represented in the network. The graph partition method also aims for an equal size of communities, which also contradicts the constraint "a".

Therefore, in this paper, the authors chose the modularity maximization algorithm, in particular, the Clauset–Newman–Moore greedy modularity maximization, whose implementation is presented in the networkx library [54].

The input data are the combinability graph shown in Figure 4. It is filtered according to the external factors present and then passed to the input of the modularity maximization algorithm.

The algorithm chooses the subgraphs of the initial graph G so that the modularity parameter (1) [55] is maximized. The following is a formula for the modularity parameter:

$$Q(\gamma) = \frac{1}{2m}\sum_{ij}(A_{ij} - \gamma\frac{k_i k_j}{2m})\delta_{g_i g_j} \quad (1)$$

where m is the number of edges in the network, k is the degree of nodes i and j accordingly, A_{ij} is the number of edges in the group, δ_{ij} is the Kronecker δ, and γ is the modularity resolution.

The main adjustable parameter of this algorithm is the resolution parameter γ, the correct choice of which depends on the quality of selection of graph components and respectively formation of assortments. Determination of the optimal value of the resolution parameter was performed experimentally. For this purpose, on the basis of the initial graph of combinability shown in Figure 4, synthetic subgraphs for all possible combinations of limiting factors were formed in an amount of 448 variants. For each option (subgraph), communities were generated using a modularity maximization algorithm with different variants of resolution parameter in the range from 0.1 to 2 with step of 0.1. Comparison of subgraphs for each resolution parameter was based on compositional improvement index (2), the difference between the proportion of nodes retained and the proportion of remaining negative links.

$$O = \frac{n_b}{n_a} - \frac{e_b}{e_a} \quad (2)$$

where n is the number of nodes; e is the number of negative links; a and b are in the conditions before and after the algorithm, respectively. Results of this comparison are demonstrated in Figure 11.

Based on the results obtained, it can be concluded that on average, the best value of the resolution parameter for all variants of subgraphs is resolution 1.0.

4.3. Generation of Final Assortments Based on the Modularity Maximization Algorithm

The final step is the formation and selection of assortments based on co-occurrence.

Figure 12 shows the variants of plant species assortments for Saltykov-Shchedrin Garden and Benois Garden. For Saltykov-Shchedrin, in the first variant, most of the augmented species, with the exception of species 355, 357, 523 and 524 (*Rosa cinnamomea* L., *Rosa gallica* L., *Rosa* *acicularis* Lindl., *Rosa canina* L., respectively), have no conflicts with already-growing plant species. In the second variant, there is a negative relationship, but a positive relationship is formed between species 504 (*Tilia cordata* Mill.) and the five augmented species, which can be used by the landscape architect in the formation of the arboretum.

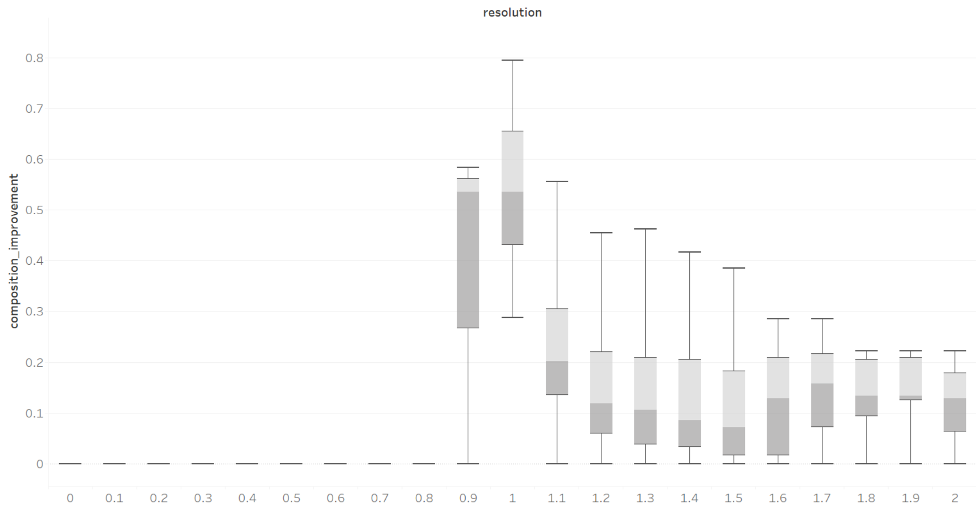


Figure 12. Distribution of compositional improvement index values for all subgraph variants within the selected range of variation of the resolution parameter.

For Benois Garden, the recommended options are smaller, due to the more stringent constraints of the terrain. However, they do not have a negative relationship within the composition, and the former is more varied (50% trees, 30% shrubs and 20% perennial grasses) than the original version (95% trees and 5% shrubs).

5. Discussion

The validation of the algorithm shows that it can be applied in a number of scenarios. They are graded according to the information available for use from a polygon with the boundaries of the area being gardened (in this case, spatial data containing information about some external factors can be generated on the basis of open data) to a complete list of plant species existing on the territory and the factors affecting them.

The novelty of the proposed approach lies in the application of spatial modeling and network analysis methods to generate a list of sustainable plant compositions in the context of St. Petersburg. At the same time, the method is planned to be tested on other urban green spaces in future works. It should be noted that in its current form, the method has a number of limitations. In particular, when applied to an area with an existing set of species, a large number of negative relations are retained. If the method is used for new landscaping, a large number of external limiting factors strongly reduce the final number of suitable species, as can be seen in Figure 13. These problems can be solved by determining the significance of external and internal factors based on experiments with a graph model, further enriched with facts from the scientific literature. Nevertheless, the proposed method can adapt the urban greening management system to the climate change process by better accounting for the influence of external factors (e.g., soil waterlogging or stronger winds) on landscaping and the selection of plant species resistant to these factors. In addition, the method can increase the diversity of species in an area, which also leads to a more resilient urban ecosystem.

It should be noted that the authors see the main value of the tool presented in the article in assisting young architects, as well as in planning landscaping for areas where a landscape architecture specialist would not be involved due to the small scale and specificity of the areas. This applies in particular to boulevards, technical planting areas, and other landscaping areas not traditionally the domain of landscape architects. It should also be noted that the result of forming the assortments of plant species significantly depends on the choice of algorithm for subgraph selection and the choice of initial conditions for this algorithm. In this article, the authors have used one of many possible ways of designing subgraphs. In this regard, the authors would be grateful to all those willing to join this study in terms of conducting experiments on the generated graph of plant species, as well as in supplementing this graph [56]. Another factor that requires a separate discussion is the definition of the type of plant interactions. It should be borne in mind that this is an evolving field, and the presence of plant species interactions is determined by the degree to which the interactions between species have been studied. In this work, where the influence was unknown, it was noted as neutral, which of course has an impact on the final assortments.

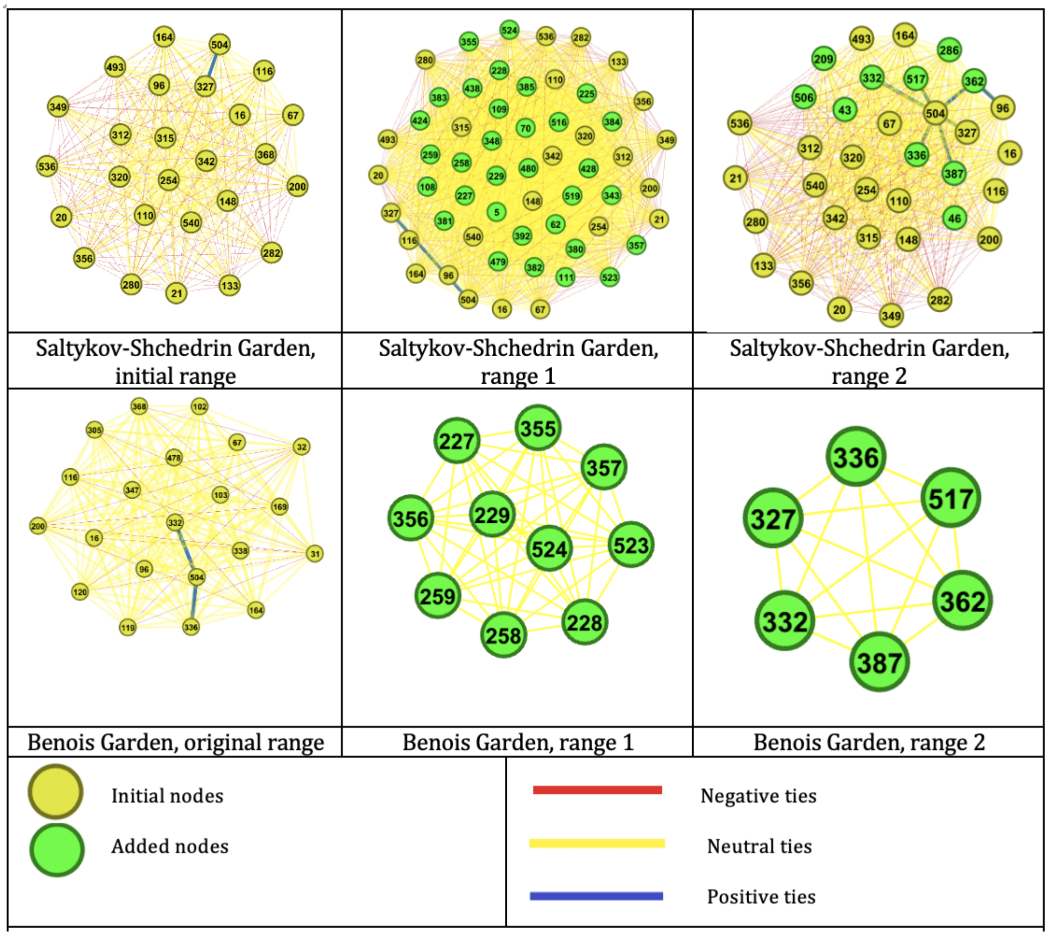


Figure 13. Recommended range of plant species for Saltykov-Shchedrin Garden and Benois Garden.

6. Conclusions

In the present article, the approach to the automation of the formation of variants of assortments of plant species for territories with known conditions of growth of plants taking into account the mutual influence of plants and existing precedents of joint occurrence of plant species is considered. On the basis of an algorithm, the device for modeling graphs for kinds of plants, which has allowed one to take into account the facts of positive and negative mutual influence of kinds of plants operating with parameters of tops and edges of a graph, is used. The implementation of the approach required the formation of a plant species base, taking into account the growing conditions of species, in addition, taking into account the precedents of species co-occurrence required an inventory of existing greenery plantations. The resulting graph and species database, however, made it possible to implement methods for automatically generating stable assortments of plant species for given areas. The final assortments were generated using a modularity maximization method over the generated plant graph, excluding species unable to grow in the given conditions. The best parameters of the modularity maximization method were determined experimentally and were used to demonstrate the approach in two green areas of St. Petersburg, namely Benois Garden and Saltykov-Shchedrin Garden. The results of applying the method to the areas chosen for the demonstration have shown that it is possible to form both main and complementary plant assortments with no negative relationships or with new positive relationships to existing plant species. This shows the applicability of the method not only for the automatic generation of assortments, but also its usefulness for landscape architects in planning the development of species composition for relatively large landscaping areas 4.

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