The Environmental Effects of Urban Greening: Modeling Carbon Dioxide Absorption

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Keywords: CO_2 absorption, Assimilation potential, Urban ecosystem, Urban greening, Sustainable development goals.

Abstract: The greening of urban territories is an important component of improving the human habitat in conditions of almost worldwide ecological crisis. Such factors as the gaps in the existing general methodology, the lack of consideration of the decreasing life cycle and productivity of plants in a human-transformed environment, etc. complicate the green spaces' environmental efficiency assessment. This study aims to develop a model for the absorption of technogenic emissions, in particular carbon dioxide, by green plants, e.g., ash trees (Fraxinus Excelsior). The obtained results are relevant for environmental protection and urban planning services when planning the improvement and environmental rehabilitation of local territories.

1 INTRODUCTION

The rapid growth of the Earth's population causes a significant increase in the intensity of anthropogenic impacts on the environment. The development of industry, construction, and other economic sectors inevitably leads to contamination of the planet's shells, disruption of natural landscapes, waste generation, etc. Human economic activity is also the reason for the changes in climatic conditions, in particular global warming, which various authors (Kabir et al., 2023; Tarafdar et al., 2023) associate with an increase in emissions of so-called “greenhouse gases” (GHG). In this regard, the problem of ensuring and maintaining the quality of human habitat at a favorable level is becoming increasingly urgent. (Ovchinnikova, 2023).

Greening is one of the ways to ecologically heal the human habitat, especially in highly urbanized areas. Apart from aesthetic factors, green spaces influence the microclimate of local territories, reduce the level of anthropogenic noise, and absorb the pollutants and GHG (Andersson-Sköld et al., 2018; Badalyan et al., 2022; Nicese et al., 2021). The aim of this research is to evaluate the environmental efficiency of urban greening. The green plants' ability to absorb carbon dioxide is the object of the represented study.

The review of current works on the investigated topic (Ariluoma et al., 2021; Beets et al., 2012; Behera et al., 2017; Boukili et al., 2017; Chan et al., 2018) has revealed that studies on vegetation's ability to absorb and sequester carbon tend to be conducted empirically, often in natural forests and reserves. Thus, the obtained results do not consider the changes in the taxation indicators of tree stands influenced by a human-transformed environment. The presented study proposes a more general approach based on the analysis of the known indicators of growth and biological productivity of green stands, with consideration of the reduction of their life expectancy in the urban ecosystem.

2 MATERIALS AND METHODS

As a criterion for evaluating the effectiveness of increasing the “greening” of urban areas, it is proposed to use the assimilation potential of the ecosystem in relation to carbon dioxide. The assimilation potential here refers to the ability of structural elements of the natural environment, in this

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case, green spaces, to absorb the substance in question. The subject of evaluation is the simulated ecosystem of urban territory (Badalyan et al., 2017), which is the idealized (abstract) site accommodating the optimal number of higher-order plants of one species (monoculture) in terms of preservation and maintaining assimilation potential. The studies of climatic and anthropogenic conditions, along with the biodiversity and adaptability of species in the examined area, are the basis for choosing monoculture for modeling simulation.

A key feature of the proposed model is consideration of the difference between the taxation indicators of natural tree stands and plants of the same species that grow in the urban environment. The significant decline in the tree stands' lifespan due to technogenic impacts (Badalyan et al., 2017; Stepanenko, 2015) makes it necessary to consider the drop rate increase in the annual gains in the tree phytomass in the human-transformed environment in comparison with a natural one. The analysis of the dendrometric characteristics of the monoculture allows for the determination of the numerical dependencies between their biotic features and their age. This, in turn, will provide the opportunity to predict the impacts of green spaces on the state of ecosystems (Badalyan et al., 2022).

The environmental efficiency evaluation of the enlargement of the green space areas is carried out according to the following algorithm.

2.1 Defining the Initial Conditions

The model input is the number of adopted monoculture saplings additionally planted in the territory (ΔN).

The following parameters of tree stands are relevant for the goals of the given research:

- increase in the phytomass stock (m_{ph}), t/ha,
- gross primary productivity (GPP), i.e., the mass of organic matter generated as a result of photosynthesis, which is measured in mass units of carbon per area unit, kg C/ha;
- net primary productivity (NPP), which is the mass of organic matter that replenishes directly the stock of phytomass, kg C/m^2.

2.2 Determining the Size of the Optimal Planting Area

The area occupied by additional green plants can be calculated according to the formula:

$$\Delta S_g = \Delta N \cdot S_1, \quad (1)$$

where S_1 is the area necessary for the optimal growth of a single tree, m^2.

Defining the optimal tree number in the territory with the use of the growth tables is necessary for ensuring the best productivity of the green plants during their whole lifespan. The criterion of selection is the number of full tree stands with site indices Ia and I for the age of maximal growth of their crowns. (Badalyan et al., 2017; Shvidenko et al., 2008). Thus, the necessary area for the optimal growth of one sapling can be calculated as:

$$S_1 = \frac{1}{Nk_d}, \quad (2)$$

where N is the optimal tree number, ha^{-1}, and k_d is the crown density factor.

2.3 Calculating Parameters of Productivity

The productivity parameters of the monoculture in the added area are suggested to calculate with the use of the formula

$$\Delta X_T = X_T \cdot \Delta S_g, \quad (3)$$

where X_T – is the productivity characteristic (m_{ph}, GPP или NPP) for the monoculture of the age of T, and ΔX_T is the respective characteristic in the added area ΔS_g.

The trends of average annual gains in phytomass, GPP, and NPP tailored to the more rapid aging of tree stands in the human-transformed environment are defined with the use of the method (Badalyan et al., 2017, 2022) and the tables of biological productivity (Shvidenko et al., 2008). These dynamics are expressed in the analytical dependencies identified by the regression analysis methods.

2.4 Estimating the Mass of Carbon Dioxide Absorbed by Additional Green Plants

By reducing the complex process of physicochemical transformations occurring in the metabolism of autotrophs to glucose breakdown, it is possible to determine, with sufficient accuracy for estimation, the masses of CO_2 uptake through photosynthesis and its release through respiration. The difference between these values characterizes the ability of an ecosystem to sequester CO_2.

$$\Delta AP = \Delta m_p - \Delta m_e, \quad (4)$$

where ΔAP is the added assimilation potential stemming from additional green planting, t, Δm_p is the added tree stands' CO_2 uptake through photosynthesis, t, and Δm_e is the mass of CO_2 exhausted through the added trees' respiration.

Let us take a detailed look at the photosynthesis equation.

$$6CO_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{h\nu} C_6H_{12}O_6 + 6O_2. \quad (5)$$

The mass of glucose formed in the process of photosynthesis can be recovered from the GPP value using the formula

$$\Delta m_{C6H12O6} = \frac{\Delta GPP}{\omega(C)}, \quad (6)$$

where $\omega(C)$ is the mass share of carbon in the glucose molecule.

Then the mass of reacting CO_2 can be calculated with the help of equation (5).

$$\Delta m_p = \Delta m_{C6H12O6} \cdot \frac{\nu \cdot M(CO_2)}{M(C_6H_{12}O_6)}, \quad (7)$$

where ν is the number of CO_2 molecules in the expression (5), mol, $M(CO_2)$ and $M(C_6H_{12}O_6)$ are the respective molar masses of carbon dioxide and glucose, g/mol.

Similarly, the mass of broken-down organic matter (glucose) and then the value of Δm_e are determined from the autotrophic respiration equation (8):

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 2.87 \cdot 10^6 \text{ J}, \quad (8)$$

$$\Delta m_{C6H12O6} = \frac{\Delta Ra}{\omega(C)}, \quad (9)$$

where ΔRa is the mass of carbon in the organic matter (glucose) that breaks down in the respiration process, kg C;

$$\Delta Ra = \Delta GPP - \Delta NPP, \quad (10)$$

$$\Delta m_e = \Delta m_{C6H12O6} \cdot \frac{\nu \cdot M(CO_2)}{M(C_6H_{12}O_6)}. \quad (11)$$

It makes sense to evaluate the effectiveness of increasing the assimilation potential of the ecosystem on a long-term scale. In this case, the ecological effect from the enlargement of green space areas (the amount of CO_2 sequestered) is calculated by integrating the approximated $\Delta AP(T)$ function over the lifetime of the tree stand in the urban ecosystem:

$$\Delta AP_T = \int_0^T \Delta AP(T)\,dT. \quad (12)$$

The parameter of specific productivity of the examined monoculture's assimilation potential that characterizes the species' ability to absorb and sequester carbon dioxide can thus be calculated using the expression

$$\delta_a(T) = \frac{\Delta AP(T)}{\Delta s_g}. \quad (13)$$

3 RESULTS AND DISCUSSIONS

The subject of the study is an ecosystem simulation based on the *Fraxinus Excelsior* monoculture (Badalyan et al., 2017, 2022). The environmental impact of the enlargement of green space areas in the urban ecosystem is proposed to be considered in terms of the additional planting of 1000 ash saplings in the model ecosystem. Using the *Fraxinus excelsior* growth tables (Shvidenko et al., 2008) , we have determined the range of optimal tree number in the area of 1 ha N = (1649 – 4866) ha^{-1}. Then, with the coefficient of crown density k_d assumed to be 0.6 for an urban environment, the area necessary for maintaining the optimal growth of a single sapling ranges from 3.43 to 10.11 m^2. Considering the studies (Badalyan et al., 2017, 2022) S_1 was set at 7,2 m^2, hence the additional planting area ΔS_g is 0,72 ha.

Using the productivity models for the average site index of *Fraxinus Excelsior* (Shvidenko et al., 2008) the analytical dependencies of productivity parameters on the age of tree stands under anthropogenic impact were determined through the implementation of regression analysis methods.

$$m(T) = 3.547 \cdot 10^{-4}T^3 - 0.086T^2 + 6.089T - 8.595, \quad R^2 = 0.9846; \quad (14)$$

$$GPP(T) = \frac{-5.75\cdot10^{6} + 9.42\cdot10^{5}T + 5.354\cdot10^{4}T^{2}}{1+1.518\cdot10^{4}T + 1.461\cdot10^{3}T^{2}} \quad (15)$$

$$R^2 = 1;$$

$$NPP(T) = -2.614\cdot10^{-4}\cdot T^2 + 0.04T + 0.094, \quad (16)$$

$$R^2 = 0.9821.$$

The indicators of added productivity of the model ecosystem were defined through the formula (3), considering monoculture growth in a human-transformed environment (Table 1). The foundations for the calculation are the Fraxinus Excelsior productivity models for the average site index and previous studies (Badalyan et al., 2022).

Table 1: The additional productivity of *Fraxinus Excelsior* simulative ecosystem.

T, years	Δm_{ph}, t	ΔGPP, tC	ΔNPP, kgC
5	6.008	1.9	0.24
20	58.768	27.977	0.568
40	86.447	28.752	0.919
60	89.107	28.415	1.118
65	87.3	28.328	1.145

Data on the added assimilation potential for carbon dioxide were obtained using formulas (4–11). The dynamics of changes in the added assimilation potential with the age of the stand are shown in Figure 1. These data, calculated using the regression analysis methods, allow determining the analytical dependence.

$$\Delta AP(T) = -0.00067T^2 + 0.104T + 0.271, \quad (17)$$

$$R^2 = 1.$$

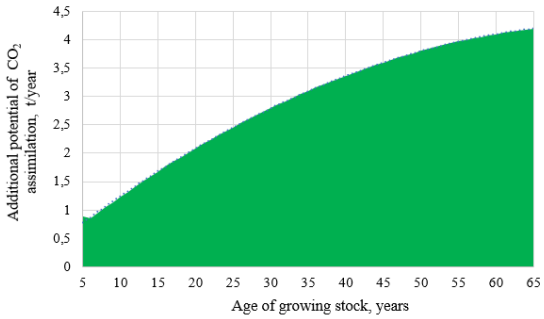

Figure 1: The long-term dynamics of additional assimilation potential of simulative ecosystem.

The amount of CO_2 absorbed by additional green spaces during their lifetime in an urban environment is determined by the integration of function (17) within 5 – 65 years and amounts to 172.971 tons.

The specific carbon dioxide assimilation potential for Fraxinus excelsior was determined from the expression (13) for each year of plant life in a human-transformed environment (Fig. 2). It becomes obvious that this indicator increases with age and varies quite widely from 1 to 6 t/ha per year.

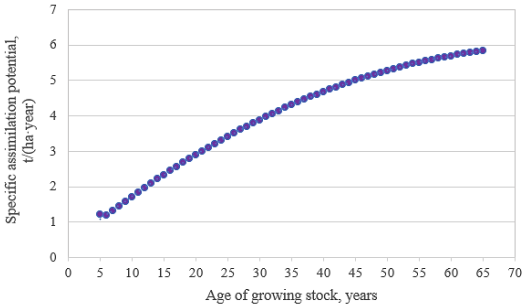

Figure 2: The specific CO_2 assimilation potential of Fraxinus Excelsior.

Thus, greening the urban environment by planting ash trees will increase its assimilation potential in relation to both carbon dioxide and other pollutants.

4 CONCLUSIONS

Sustainable development of urbanized territories is impossible without establishing and maintaining a favorable environment. The greening of urban areas is an important step in the rehabilitation of landscapes under technogenic pressure. The obtained results mathematically express the ability of green spaces to absorb CO_2 in a human-transformed growing environment. It can be concluded with confidence that the ecological efficiency of green spaces increases with the age of tree stands. Therefore, landscaping the territory can be considered a long-term investment in improving the habitat and, consequently, another step in achieving the goals of sustainable development in local territories.

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