Carbon-sequestering and oxygen-producing functions of urban forests of Kyiv city and pre-urban forests of Stockholm city

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Master thesis in Forest Management, Euroforester master program
SLU course code EX0506 Advanced level(E) 30ECTS (HEC)

Abstract

Interest to carbon-sequestering and oxygen-producing functions of forest has risen considerably during last decades. Abovementioned functions of forest ecosystems acquire special significance in pre-urban and urban forests. These forests perform not only stabilizing and protective functions, but also are a renewable resource. Due to rapid development of modern technologies (bioenergy), the latter named feature becomes more and more important. However, currently there is practically no one scientifically based assessment of abovementioned functions of pre-urban forests, especially in comparison with other regions and countries.

The main aim of this study was to assess and quantify carbon sequestration and production of oxygen of selected parts of urban forests of Kyiv city and pre-urban forests of Stockholm city, and to compare the results.

Within this study, techniques developed by P. Lakyda (computation of phytomass and sequestered carbon) and N. Tshesnokov and V. Dolgosheev (estimation of oxygen productivity of forests) were applied. Authors have encountered numerous “compatibility problems” with the technique used and the initial datasets. Nevertheless, majority of the problems were solved successfully, thus enabling accomplishment of the main aim. This research is important as a test of compatibility of different methodologies and datasets, and provides quantitative estimation of carbon-sequestering and oxygen-producing functions of the studied forests.

Keywords: carbon sequestration, urban and pre-urban forests oxygen production, estimation, compatibility.

Реферат

Інтерес до вуглецедепонувальних та киснепродукувальних функцій лісу істотно зріс протягом останніх десятиліть. Названі функції лісових екосистем набувають особливої важливості у приміських та міських лісах. Ці ліси виконують не лише стабілізуючу та захисну функції, вони також є відновлюваним ресурсом. У зв'язку зі швидким розвитком сучасних технологій (біоенергетики), остання особливість лісів стає все більш і більш важливою. Втім, на даний час науково обґрунтовані оцінки вищезгаданих функцій приміських і міських лісів, особливо у порівнянні з іншими регіонами чи країнами, практично відсутні.

Основним завданням даного дослідження було кількісне оцінювання депонування вуглецю та продукування кисню частиною міських лісів м. Києва та частиною приміських лісів м. Стокгольма, а також порівняння отриманих результатів.

У ході дослідження використано методики Лакиди П.І. (розрахунок фітомаси лісів та депонованого у ній вуглецю) і Чеснокова Н.І. та Долгошеєва В.М. (оцінювання киснепродукувальної функції лісових насаджень). При цьому автор зіткнувся зі значною кількістю «проблем сумісності» дослідних даних і методик з різних країн. Втім, більшість названих труднощів були успішно подолані, а основні завдання дослідження – виконані. Практична цінність даної роботи полягає у тестуванні сумісності методик та дослідних даних і здійсненні кількісної оцінки вуглецедепонувальних та киснепродукувальних функцій досліджуваних лісів.

Ключові слова: міські та приміські ліси, депонування вуглецю, продукування кисню, оцінювання, сумісність.

Content

1. Introduction

Development of mankind is characterized by major negative influence upon environment. Human activities have led to environmental changes, which resulted in soil erosion, floods, decrease of percentage of forest land, deterioration of natural resources, diminution of biodiversity, carbon misbalance, destruction of ozone layer, global climate change, contamination of environment with radionuclide and so forth.

Forest, one of the most important biosphere components, is capable of sustaining ecological balance. Its stabilizing role is the most evident in those places, which have been exposed to rather intensive anthropogenic influence. Good examples of this kind of exposure are urban forests in large cities. Urban forests are very important in terms of water protection and they purify the atmosphere, since they sequester carbon and act as a source of oxygen. Therefore protection, rational use and expansion of forest resources are vital, since they mitigate these problems and become especially important in urban and pre-urban forests.

1.1. Main considerations for choosing a study object

Within the transition of global forestry to sustainable development basis, it is very important to investigate ecological, economical and social aspects of forest objects. Forests, which are located within the borders and (or) nearby urban settlements, (i) are commonly used for recreation of urban inhabitants, (ii) holding cultural and curative activities and (iii) for keeping favorable ecological conditions. These forests are complex and have diverse nature and are crucial for sustaining urban environment stability functions (Federal agency of forestry of Russian Federation, 2009).

Part of urban forests of Kyiv and a part of pre-urban forests of Stockholm were chosen as objects in this study by following reasons:

1. Fragmentary studies of carbon-sequestering functions of urban and pre-urban forests;
2. Lack of studies of oxygen-producing functions of urban forests;

3. Importance of forests as a part of social infrastructure and their functions for sustaining urban environment stability.

1.2. Characteristic and comparison of study objects and their geographical locations

Characteristic of location of chosen part of urban forests of Kyiv (Communal enterprise "Darnytsya forest-park economy")

Communal enterprise "Darnytsya forest-park economy" (further referred to as Kyiv sample) is situated in the central part of Kyiv region (oblast') in the territory of Desnyansky, Dniprovsky and Darnytsky regions of Kyiv, Brovary region of Kyiv oblast' and Brovary town. The enterprise has five forest management units with a total area of 16569 hectares. Percentage of forest land of the communal enterprise in the region is 24,5% (Ukrderzhlisproekt, 1999).

*Figure 1.*Geographical position of Darnytsya forest-park economy (point A).

The territory of Darnytsya forest-park economy is a part of southern zone of Ukrainian Polissya and borders with Forest-Steppe zone. The climate is characterized as mild, with relatively high average annual temperatures (+6,7 °C) and an annual precipitation ranging from 400 to 800 mm. Duration of frost-free period averages to 180-187 days, where the precipitation during this period equals to ca. 380 mm (65 percent of total annual precipitation) (Ukrderzhlisproekt, 1999). In general, climate gives favorable growth conditions for different tree and bushy species (pine, oak, birch, alder, hazel, rowan, buckthorn, elder etc.) and possibilities to introduce valuable species. This statement is confirmed by presence of highly productive stands of main forest-forming tree species.

Geomorphologically, the region is located on the watershed of Dniproriver in Kyiv Polissya zone. Forest stands are situated on indigenous plateaus, flood plains and river terraces. Surface of Kyiv Polissya has small north-eastern inclination. On the south Kyiv Polissyais separated from forest province by marked ledge. When moving to the north, the terrain becomes more flat. The most widespread type of soils are podzols (sod-podzolic sub-types), while other soil types (grey, sod, chernozem, bog) with various mechanical composition and physicochemical properties are much less common.

An enterprise is located in Dnipro and Desna river basin. Level of drainage in the territory is considered to be satisfactory. Ground water line depth varies from 1,5 to 25 meters. The majority of soils are characterized as mesic soil moisture (Ukrderzhlisproekt, 1999).

Economical activity of an enterprise is concentrated on improving flood control, recreational values, protecting biodiversity and other useful natural functions for sustaining public health and improving ecological situation. Another field of enterprise' activity is rational use of forest resources in order to provide the population with timber and other forest resources and utilities; improve species composition and wood quality of stands; maintain forest fire protection as well as pests and diseases control; rational use of land fund in order to organize recreation for population of Kyiv city.

Characteristic of location of chosen part of pre-urban forests of Stockholm (Huddinge)

Huddinge municipality (Huddinge kommun, further referred to as Stockholm sample) islocated in the southern region of Stockholm county in central Sweden. Its seat is located in Huddinge, which is a part of Stockholm urban area. The municipality covers the central part of the Södertörn peninsula. More than half of the land area consists of hills, lakes, agriculture- and forestland, and it contains seven nature reserves.

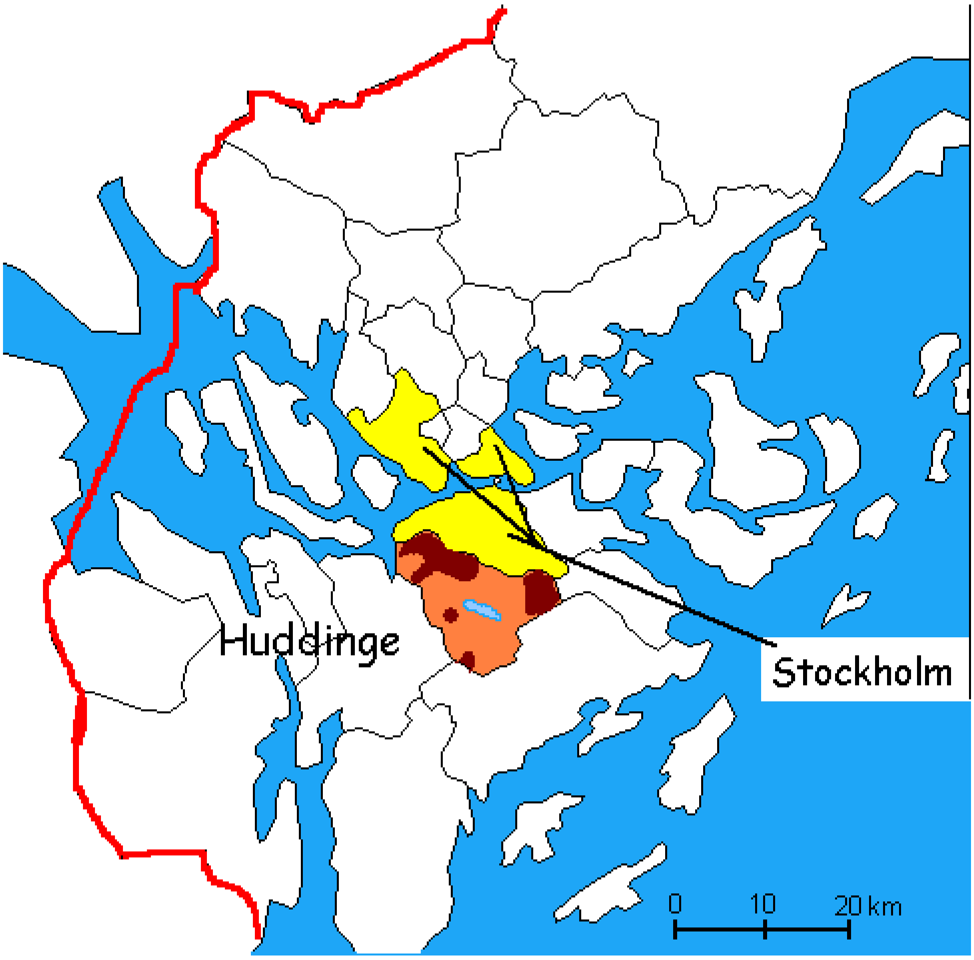

*Figure 2.*Geographical position of studied part of pre-urban forests of Stockholm (Huddinge).

Stockholm has a humid continental climate according to the Köppen climate classification (Peel, Finlayson, McMahon, 2007). As an effect of the high latitude, daylight varies widely from more than 18 hours in midsummer, to approximately 6 hours in late December.

Despite its location, Stockholm has relatively mild temperatures and much warmer and more sun hours throughout the year, compared with other places at similar latitude, mainly because of the influence of the Gulf Stream. The city has 1981 sun hours as an annual average.

Summers are warm and pleasant with average mid-day temperatures of 20–23 °C and lows of around 15 °C, but temperatures frequently exceed 25 °C. Winters are cold with average temperatures ranging from -3 to 1 °C, and rarely drop below −10 °C. Spring and autumn are generally cool to mild (SMHI, 2010).

Annual average precipitation is 539 mm with 164 (World Weather Information Service, 2008) wet days of light to moderate rainfall throughout the year. Snow mainly occurs from December through March, but recent winters have tended to be free of snow.

Comparison of study objects and their geographical locations

The data in table 1.1 proves that despite of rather favorable and relatively equal climatic conditions, and due to greater difference in soil conditions leads to more favorable forest growing conditions in Kyiv than in Stockholm. The comparison is provided in table 1.1

Table 1.1 Comparison of study objects and their geographical locations.

Comparison parameters	Kyiv	Stockholm
Forested land, 10^3 of ha	15,3	3,4
Growing stock, 10^6 of m^3	5,4	0,5
Dominant tree species	pine, oak, birch, alder	spruce, pine, birch
Annual precipitation, mm	400-800	539
Average annual temperatures, °C	+ 6,7	+ 6,8
Forest growing conditions	rich	average

1.3. Main aim and goals of study

The main aim of this study is to assess and quantify carbon sequestration and production of oxygen of selected parts of urban forests of Kyiv city and pre-urban forests of Stockholm city. In order to attain this aim, we have conducted the following studies:

- analyze and check the compatibility of initial dataset and methodology of study;
- analyze the influence of forestry practices upon carbon-sequestering and oxygen-producing functions of forests;
- point out possibilities for improving existing methodology of assessment of abovementioned functions of forests;
- give recommendations for improving performance of functions of urban and pre-urban forests, connected with biomass production.

Abovementioned goals can be achieved by processing initial data, information from specific literature and analysis of results and their main causes.

2. Literature review

Processes of carbon deposition and oxygen production are inseparably linked with biomass production of forests. It is worthwhile to start studying problems, outlined in the first chapter of this work, from short overview of historical groundwork and current approaches and methods of research of biomass production in forests.

2.1. Terminological and theoretical basis for studying biomass production of forests and its components

According to data provided by FAO, total area of forests in the world is equal to 3,95billions of hectares. Percentage of forest land is 30% (State of the World's Forests, 2007). Phytomass created by world forests makes up 60% of total phytomass, produced by all ecosystems of the planet (Ukrainian encyclopedia of forestry, 1999).

The leading factor of carbon redistribution is activity of live matter of a planet, which keeps up the complicated system of geochemical regulation, prearranges its relative stability and possibility for existence of life on Earth. The concept of "live matter" was introduced by V.I. Vernadsky, who treated it as totality of all live organisms of a planet (Vernadsky, 1926).

Carbon budget and oxygen productivity of forest stands are tightly connected with biomass production in forest. The main stimulus for the start of large-scale work aimed at studying forests' bioproductivity was performing tasks of International biology programme, which was approved in Paris in 1964. This programme appeared as an answer to risk of resources shortage as an effect of rapid increase of world population.

It is worthwhile to pay special attention to studies of bioproductivity of forest phytocoenoses done by V.K. Myakushko(1972). His investigations are important from the point of view of mainly biology and forestry. He ascertained that phytomass accumulation in forest phytocoenoses increases from dry to fresh and moist conditions and slightly decreases in damp and wet site conditions.

Examining productivity and phytomass structure as a complex problem and basing upon main principles of system approach, P.I. Lakyda (Lakyda, 2007; Lakyda, 2006; Lakida et al., 1995; Lakida et al., 1996) developed mathematical models and normatives for assessing phytomass components of Scots pine in conditions of Polissya, Lisostep and Lower Dnipro sands; Pedunculate oak in conditions of Polissya and Lisostep; for spruce and beech stands of Carpathians. Detailed studies of bioproductivity of individual tree species were done by scientists of his scientific school.

Studying productivity and structure of stand phytomass is a complex problem, which forms subject of investigation of many scientific disciplines: ecology, silviculture, forest mensuration and so forth. Such investigations were conducted but never completed in a study of forest biogeocoenoses on the side of general investigation of their structure and functioning. Until recently, there were two main areas of studying phytomass as main component of forest bioproductivity (Pozdnyakov, 1973):

- *biogeocoenologic* (ecologic), which studies regularities of accumulation and circulation of matter and energy in phytocoenosis;
- *resource-science,* which stipulates forest phytomass assessment as resource potential of forest sector by needed components for economics.

Three of the most widepread methods of stand phytomass assessment are pointed out (Satoo, 1962; Satoo, 1966):

1) *method of an average tree,* which is insufficiently accurate, especially when assessing crown phytomass due to a fact that average trees by diameter re not usually average by other mensurational indices;
2) *method of relation of basal areas of model trees and a stand,* which is more accurate than the previous one n case of thorough selection of model trees by diameter and height of stem, length, density and diameter of crown;
3) *regression* method, which is now regarded as the most universal and precise. According to this method, model trees are selected in a way to proportionally represent main population of trees by diameter and, more rarely,

by height. Afterwards, initial dataset is equalized analytically by the means of regression analysis.

Precision of estimates of phytomass depends not only on sampling method and quantity of model trees, but also time of year, weather conditions, ways of separation of components, methods of measuring and weighing (Babich, 2004). These factors explain different variation of acquired phytomass indices, which is conditioned (i) by different percentage of annual increment in total mass of fractions, (ii) by different moisture content in phytomass fractions and (iii) by precision of methods of model branches of crown sampling and processes of measuring and weighing. So it is necessary to keep in mind that the correctness of applied methods has to be reasonable and it is necessary to correlate needed correctness with factual precision and required precision to still have a possibility to implement the results in practice.

Today big amounts of information on phytomass stock parameters are accumulated by virtue of scientists in different countries. Nevertheless, as it was before, one of typical biometrical tasks is estimating biomass production of trees and stands by main phytomass components in weight units and developing corresponding normatives. Existing methodologies for assessing phytomass components of trees and stands are possible to separate by approaches:

- *weight method* involves weighing tree phytomass fractions in the forest and taking samples for determining moisture content;
- *stereometric method* includes measuring volumetric indices of stem and branches with further re-calculation to mass units using indices of wood and bark density;
- *complex method* combines weight and stereometric methods;
- *pipe-model method* is based on estimating components of tree crown phytomass based on theories of balanced system of xylem water transport of plants;
- *aerospace methods* aim on finding stochastic relations between decoded tree and stand indices and corresponding phytomass parameters;

- *method of generalization* rests upon analyzing published studies for different regions and deriving needed normative for assessing separate fractions of phytomass and bioproductivity of stands;
- *use of GIS-systems and technologies* is a rather new and high-technology method which is based upon use of modern findings in the sphere of information technologies and GIS-systems (Atroschenko, 1999).

Studies of forest biomass production (in Ukraine, Sweden and other countries) have been performed for a long time with focus to increase stand productivity, to increase the standing stock of stemwood per area unit. Today forest is regarded not only as a source of timber and pulpwood, but also to sequester carbon and as a renewable energy source (Stupak et al., 2007).

Based on the performed analysis of studies of stand biomass production, it is possible to contend the great knowledge and experience of studying forest stand productivity by phytomass components. A significant part of it was done from a resource-science point of view, for different geographical zones, which resulted in some non-comparability of results.

2.2. Forest and global climate change

Sustaining climatic system stability is one of the most important global political and economical problems. Climate change is, possibly, the most important and complicated problem of nature protection during the last century. Signing UN Framework Convention on climate change in June 1992 by representatives of 155 countries testifies that this problem is really important for the mankind. Currently the Convention is ratified by 194 parties (UNFCCC, 2010).

Main mechanisms of sustaining relative stability of air temperature on the Earth are solar radiation and greenhouse effect. Thirty percent of solar energy (short wave) that reaches the Earth is reflected back to the space. If the rest of energy (70%), which is absorbed as infrared radiation by water vapor, clouds and soils, is reflected to space, then temperature on the Earth would be equal to -18 °C. Reflection of infrared radiation by Earth (mainly by water vapor and greenhouse gases) heats it up to approximately 15 °C ($\Delta T = 33$ °C).

The following chemical compositions have a share in heating effect:

- water vapor (by 62%, 20,6°C);
- carbon dioxide (by 21,8%, 7,2°C);
- ozone (by 7,3%, 2,4°C);
- nitrous oxide (by 4,2%, 1,4°C);
- methane (by 2,4%, 0,8°C);
- fluorochlorocarbons (by 2,1%, 0,7°C) (Heinrich,Hergt, 1998).

Many year environment monitoring shows pronounced trend towards increased average annual temperature. Leading scientists connect this phenomenon with increased concentration of greenhouse gases (GHG) in the atmosphere. GHG include natural (CO_2, CH_4, N_2O) and anthropogenic gases (HFCs, PFCs, SF_6). Estimates show that CO_2 is responsible for about 80% of anthropogenic greenhouse effect; methane adds another 18-19% and the rest of greenhouse gases ca. 1-2%. Anthropogenic greenhouse effect moves the climatic system towards new equilibrium with increases in average air temperature, increases in world ocean level and more frequent events with extreme weather.

Carbon dioxide is the most important greenhouse gas and it provides carbon for photosynthesis process. Atmospheric carbon dioxide lets through short-wave solar radiation, but absorbs long-wave radiation from Earth and reflects it back, creating greenhouse effect.

According to scientific investigations, doubling CO_2 amount in the atmosphere would increase average temperature by 1,5 °C: in tropics by 2 °C, in mid-latitudes by 4 °C, and in arctic regions by 8 °C (IPCC, 2007). The most important consequences of this change would be displacement of climatic zones, expansion of drought areas, narrowing subtropical areas with winter rains and decrease of precipitation in mid-latitudes with serious consequences for water supply of developed countries (Heinrich, Hergt, 1998).

During the last 100-year period concentration of CO_2 has gone up by 40% (with annual fluctuations due to CO_2 fixation by plants) and present level is the highest for the last 650000 years. The main reasons for increased concentration of carbon dioxide in the atmosphere are burning fossil fuels, production of concrete, changes in land use and decrease of forested area (Heinrich, Hergt, 1998).

Global concentrations of methane (CH_4) have increased 2,4 times compared with pre-industrial period. Main reasons for this increase are emissions from coal, oil and gas mining, emissions from landfills and emissions connected with agriculture. Global concentrations of nitrous oxide (N_2O) have increased by 20 percent comparing with pre-industrial period. Main sources of nitrous oxide emissions are agricultural operations (e.g. ploughing), burning solid fossil fuels and biomass. Halogenated hydrocarbons (HFCs), perfluorocarbons (PFCs) and sulphurhexafluoride (SF_6) are gases of anthropogenic origin, which were absent in the atmosphere until the beginning of 20th century. They originate from industrial processes, where aluminum, magnesium and halogen-containing hydrocarbons (Buravlyov, 2004).

Natural greenhouse effect on the Earth is maintained due to balance between greenhouse gases emissions and absorption. The biggest absorbers of greenhouse gases are ocean and terrestrial biomass, which share around 70% of total absorption of carbon dioxide. Forestry activities are one of the most important areas of preventing climate changes. Possibilities of use of forests for sequestering greenhouse gases are described in Kyoto Protocol. Thus, decrease of cuttings, extended reproduction and increase of productivity could greatly reduce anthropogenic impact on Earth climate.

Participation in international activities aimed at preventing climate changes sets principally new problems for forestry:

- ascertaining main directions of forestry activities in order to provide fulfillment Kyoto protocol requirements;
- assessing the potential of world forestry in sequestering greenhouse gases and connected with this possible benefits, expenses and obstacles.

Forest phytocoenoses accumulate carbon in forms of phytomass and mortmass during their lifetime. The main reservoirs for accumulation of carbon in forest ecosystems are the following:

- trees – live and dead ones (their aboveground and belowground biomass);
- understorey vegetation (undergrowth, understory (underwood) and live surface cover);
- tree waste, litter, and soil (Buksha, 2002).

Taking into consideration all the abovementioned, its worth underlining that assessing carbon-sequestering function of forests and their carbon budget can provide a nice solution in field of finding additional carbon sinks and a possibility to improve the environment.

2.3. Production of oxygen in forest

Forests are the green lungs of our planet. Recently, conditions of environmental state are worsening, which is the most evident in large cities. Therefore sanitary and hygienic, health-improving, aesthetical and other functions become more important. Ability of forests to absorb industrial emissions and to create volatile oils and oxygen are difficult or even impossible to assess economically. Positive influence, however, is felt by every urban citizen and an opinion is that forests are one of the determinant factors of urban population life quality in broad sense is legitimate.

Oxygen is being produced during photosynthesis process. Forests play the leading oxygen-producing role, their share in relation to all terrestrial vegetation biomass is around 54% and they have the highest concentration of biomass perunit area. Forest vegetation produces 10 to 15 times more oxygen than any other terrestrial phytocoenosis (Vasilyev, 1971). Importance of urban forests in developed countries with highly urbanized population is well recognized. For instance, urban forests of the United States produce enough oxygen to secure annual consumption of approximately two thirds of the country's population (Nowak, Hoehn, Crane, 2007).

Today the question of oxygen productivity in urban forests is in focus among the scientific society but very few publications on this topic are available. Thus, it is possible to state a controversial attitude among scientists to assessing the importance of the oxygen-producing function of forests. Methodologies of assessment and economical evaluation of this function are worked out. Methodology of M.I. Tshesnokov and V.M. Dolgosheev was developed in 1970's, whereoxygen productivity was calculated by means of two main indices, bone-dry phytomass and mass of oxygen, which is emitted during creation of one ton of bone-dry organic matter (Tshesnokov, Dolgosheev, 1978). Some scientists deny importance of production of oxygen and necessity to estimate and account the amounts (Sofronov, 1996).In practice, when assessing forest resources, oxygen-producing function is not taken into consideration.

It is known that there is a lack of oxygen in the atmosphere (oxygen concentration equals to 17-18% (instead of 20-21%; Eleven facts about oxygen and its lack, 2008) in big cities when air temperature is high and wind activity is low. In these conditions the importance of oxygen-producing function of urban and pre-urban forests becomes evident, as well as their role to sustain urban atmosphere stability. Hereby, when considering oxygen-producing function of forests, as a global phenomenon, arguments of those scientists who deny its importance are convincing, since forests do not create positive oxygen balance on a planetary scale. Nevertheless, when examining this question on a local level (on example of large population or industrial centers), an outstanding importance of oxygen-producing function of forest stands becomes clear. Taking into consideration everything mentioned in this sub-chapter it is possible to conclude that oxygen-producing function of forest is very important on the local scale. It is therefore necessary to conduct local monitoring and quantitative estimations.

3. Material and method

3.1. Initial data set and methodology of data processing

Estimation of overall phytomass of forests as well as carbon sequestration and oxygen production was done both for Swedish and Ukrainian datasets. The estimation was based upon generalized forest fund register of standing stock volumes on the level of forestry enterprises or territorial consolidations and calculated with a system of mathematical models which connect main phytomass components with standing stocks of studied forest stands. Although this approach gives more generalized results, it is convenient to use, since it is more efficient, clear and more user-friendly. By practical reasons it was the only way to use taking present state of informational support of Ukrainian forestry.
The source data used for performing this study were:

- materials of forest inventory of Communal enterprise “Darnytsya forest-park economy” of communal association “Kyivzelenbud” from 1999, contains information on areas and standing stocks of forested land divided into age classes, tree species and groups of forest-forming species, and site index classes;
- materials of forest inventory of a part of pre-urban forests of Stockholm city close to Huddinge town, dated 1999-2002, with an area coverage of 3350 hectares. This dataset contains stand-wise information on age, site indices, standing stock and stand composition.

Swedish dataset needed further processing and transformation in order to ensure its compatibility with methodology, which was applied for further calculations of phytomass, sequestered carbon and oxygen productivity. This methodology requires presence of site index classes by M.M. Orlov, which is a site index class defined by stand average height, age and origin (seed or vegetative). Available information on site indices linked tree species, stand age and top height. However, data on stand-wise top height was lacking in the dataset. In order to derive stand-wise information on top heights, programme SI (Hägglund, 1972, 1973, 1974) was used. This programme calculates site indices by tree species, stand age and top height, and gives out a matrix of top heights of a stand at different age. Hereby stand-wise information on top heights was derived. The next stage of dataset transformation was derivation of average heights from known top heights using regression models:

- for Norway spruce (author – Pasternak V.P., 1990):

$$H = \frac{H_t}{1.28 - 0.00223 \cdot A + \frac{3.12}{A} - \frac{18.18}{A^2}} \qquad (1);$$

- for Scots pine (author – Lakyda P.I., 1986):

$$H = 0.723 \cdot A^{0.032} \cdot H_t^{1.062} \cdot \exp^{-0.00329 \cdot H_t} \qquad (2);$$

- for Birch (author – Lishchuk M.E., 1988):

$$H = H_t^{1.049} \cdot \exp^{-0.223 - \frac{1.149}{A}} \qquad (3),$$

where H – average height of a stand;
H_t – top height of a stand;
A – age of a stand.

After all the average heights were derived, it became possible to proceed to the next phase – calculating bonity indices (site index classes) by M.M. Orlovfor every stand. In order to accomplish this step, site indices for every tree species were merged into site index classes according to bonity index scale (Normative and reference materials for forest mensuration in Ukraine and Moldavia, 1987). Results of this phase are shown in table 3.1.

Table 3.1 Merging site indices into site index classes by M.M. Orlov (Normative and reference materials for forest mensuration in Ukraine and Moldavia, 1987).

Site index classes by M.M. Orlov	Site Index (Swedish system)		
	Spruce	Pine	Birch
I^b	–	–	B26, B28, B30
I^a	–	–	B24
I	G30, G32	T30	B20, B22
II	G26, G28	T26, T28	B16, B18
III	G22, G24	T22, T24	B14
IV	G20	T18, T20	B12

Continuation of table 3.1

Site index classes by M.M. Orlov	Site Index (Swedish system)		
	Spruce	Pine	Birch
V	G16, G18	T14, T16	–
V^a	–	T10, T12	–

The next step was to transform the initial dataset and the derived indices to the form, which was needed for further calculations with specialized software (the CARBON programme). As a result, characteristics of individual parameters of forest fund of the two studied objects were obtained (see Appendix1 and 2):

1. Distribution of forested land area and stock by groups of forest-forming species(coniferous, hardwood broadleaves, softwood broadleaves);
2. Percentages of stock of main forest-forming species (pine, spruce, oak, beech, birch, aspen, alder) within the groups of forest-forming species (coniferous, hardwood broadleaves, softwood broadleaves);
3. Distribution of stocks of stands within groups of forest-forming species by age groups (young, mid-age, premature, mature and overmature (Normative and reference materials for forest mensuration in Ukraine and Moldavia, 1987);
4. Average site index classes by M.M. Orlov by groups of forest-forming species.

During data processing, maturity age for all the groups of forest-forming species was set to be equal to protective maturity age of the corresponding species (Normative and reference materials for forest mensuration in Ukraine and Moldavia, 1987). This approach was also used for distributing age classes to age groups. Average site index classes were set by M.M. Orlov's scale as weighted average values of individual site index classes to corresponding area.

Carbon sequestration and oxygen production of forests are indissolubly connected with their primary biomass production. In this study, calculation of carbon sequestration and oxygen production was based on analysis of processed phytomass data. Therefore, it is necessary to describe the algorithm of estimation of forest phytomass and deposited carbon. This algorithm was implemented by P. Lakyda in the CARBON programme (Lakyda, 1997).

The most adequate way to estimate phytomass and carbon sequestration of forests is to use large scale data of standing stock and mathematical models. Practical realization of this approach is tightly connected with finding coupling coefficients of phytomass components and stem wood volume based upon experimental data, which characterizes bioproductivity of modal forest stands (Lakyda, 1997). Calculation of conversion coefficients of phytomass fractions to standing stock of forest stands is shown below (Lakida, 1996; Lakida et al., 1995; Lakida et al., 1996):

$$Rv=Mfr/Vst, \tag{4}$$

where Rv– conversion coefficient of fraction of stand phytomass (leaves, branches, rootsetc.) to volume of stemwood, tons per cubicmeter;

Mfr – mass of certain fraction of stand phytomass, tons;

Vst – volume of stand stemwood over bark, m^3.

From this relation it was possible to estimate the fraction of stemwood over bark $Rv = Pst$, where Rv signifies base density of each phytomass component. This gave the possibility to control authenticity of sample data used for calculation of conversion coefficients. Practical application of Rv in the process of calculating phytomass components of forest stands is expressed in following equation:

$$Mfr = Vst \cdot Rv. \qquad (5)$$

Further estimation of overall phytomass of stands was accompanied with calculation of conversion coefficients *Rv* for stand phytomass components listed below (Lakyda, 1997):

Rv(f) – leaves (needles);
Rv(br) – branches (wood and bark of crown branches);
Rv(st) – stems (wood and bark of stems);
Rv(ab) – above ground phytomass of a stand;
Rv(bl) – below ground phytomass of a stand;
Rv(us)–phytomass of an understorey (undergrowth, understorey (underwood), vegetation and their root systems).
Overal stand phytomass *Rv(tot)*is calculated as a sum of listed components.

Finding analytical relations of change in *Rv* coefficients, implemented in the CARBON programme, of main phytomass components and mensurational indices of stands was done for every tree species using multiple regression method. Stand age (*A*), average height (*H*), average diameter (*D*), site index class (bonity index, *B*) and relative stand density (*P*) were considered as independent variables.

Stand age and site index class were assumed to be main independent variables in *Rv* models. Three kinds of allometric relations were used for modeling *Rv* coefficients:

$$Rv=b_0A^{b1}B^{b2}exp(b_3A), \qquad (6)$$

$$Rv= b_0A^{b1}B^{b2}, \qquad (7)$$

$$Rv= b_0A^{b1}, \qquad (8)$$

where *A*– average stand age, years;
B – site index class code;
b_0, b_1, b_2, b_3 – regression coefficients.

One of abovementioned equations (6, 7and 8) was used in every single case depending on raw data availability and mode adequacy. Equation (5) was most frequently used. However, in absence of site index data, equation (7) was used for calculating stand phytomass components.

Parameters of equations, used in this study, for estimation of conversion coefficients for phytomass fractions in stands of main forest-forming species of Ukraine, are adduced in Appendix 3.

In order to calculate an amount of sequestered carbon, mean coefficients of conversion of phytomass in bone-dry state to carbon were used. These coefficients are equal to 0,5 for wood and 0,45 for tree greenery (Matthews, 1993).

Estimation of oxygen productivity of forest stands is done using the method by Tshesnokov M.I. and Dolgosheev V.M. (1976).Oxygen productivity is calculated by way of using amount of dry matter in stand phytomass and mass of oxygen which is being emitted by a stand in process of producing one ton of dry organic matter? The latter index varies between 1393 and 1423 kilograms depending on tree species(Tshesnokov, Dolgosheev, 1976).

Hereby, making use of abovementioned materials and methods, information on amount of sequestered carbon and oxygen productivity of studied objects were derived.

3.2. Characteristic of sample data

For better understanding and to illustrate the process of biomass production in studied forests, it is worthwhile to give characteristic of sample data. Data from Sweden (Huddinge, 01.01.2000) and Ukraine (Communal enterprise "Darnytsya forest-park economy", 01.01.1999) are characterized within this section. Information on distribution of forested land and standing stock by groups of forest-forming species is given in table 3.2.

Table 3.2 Distribution of forested land and standing stock by groups of forest-forming species.

Object	Index	Total	By groups of forest-forming species		
			conifers	hardwood broadleaves	softwood broadleaves
Kyiv sample	Area, ha	15266,3	13244,9	983,5	1037,9
	Standingstock, thou. m^3	5444,0	4977,0	277,7	189,3
	Stock percentage	100,0	91,4	5,1	3,5
Stockholm sample	Area, ha	3354,6	2560,0	–	794,6
	Standingstock, thou. m^3	466,8	358,2	–	108,6
	Stock percentage	100,0	76,7	–	23,3

By analyzing information from table 3.2 it becomes clear that studied urban forests of Kyiv have bigger standing stock and occupy much bigger area than studied part of pre-urban forests of Stockholm. The dominant group of forest-forming tree species is coniferous in both cases. Hardwood broadleaved species are absent in studied pre-urban forests of Stockholm, but softwood broadleaves have considerably bigger stock in relative terms than studied urban forests of Kyiv (23,3% and 3,5% respectively). Absence of hardwood broadleaves in the studied part of pre-urban forests of Stockholm generally corresponds well with site climatic conditions. The very same factor could drive differences in terms of average growing stock per unit area (357 and 139 m^3 per ha for Kyiv and

Stockholm samples respectively). For better visualization, stock percentages of groups of forest-forming tree species are graphically depicted on Figure 3.

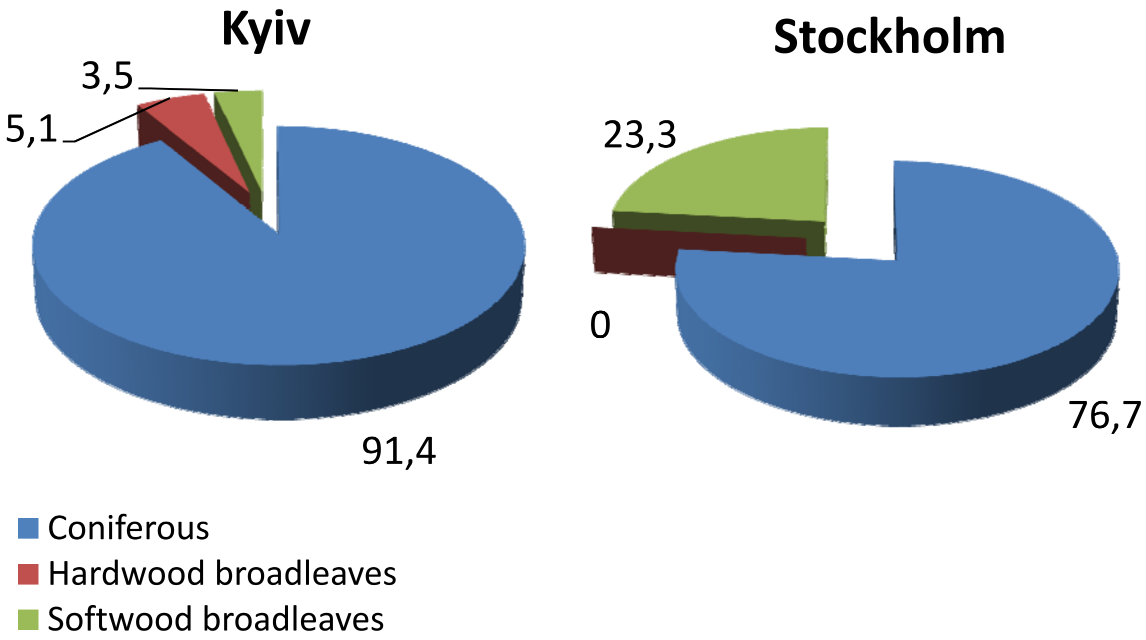

*Figure 3.*Stock percentages of groups of forest-forming tree species

Analysis of main forest-forming species relative part of standing stock (table 3.3), gives possibility to distinct differences and abundance of certain tree species of studied forests.

Table 3.3 Stock percentages of main forest-forming species within groups of forest-forming species, %.

Object	Conifers			Hardwood broadleaves			Softwood broadleaves			
	pine	spruce	other	oak	beech	other	birch	aspen	alder	other
Kyiv sample	99,7	0,3	0,0	95,8	0,1	4,1	57,7	4,5	25,1	12,7
Stockholm sample	48,0	52,0	0,0	0,0	0,0	0,0	100,0	0,0	0,0	0,0

From table 3.3 it becomes apparent that the prevailing tree species of coniferous and hardwood broadleaved groups of forest-forming species are Scots pine and Pedunculate oak respectively. In softwood broadleaved group, birch (57,7%) and black alder (25,1%) have the biggest volume share. Group of coniferous forest-forming tree species is represented, practically, by Scots pine only (99,7%). Other tree species like Norway spruce, European larch and Eastern white pine are also present in studied forests, but to minor extent. Within hardwood broadleaved group, the biggest volume share was Pedunculate oak (84,5%), while beech has very small share. Other tree species take a significant part (4,1%), from which the most significant is Black locust.

When analyzing Swedish dataset, it was possible to conclude that in coniferous group of forest-forming tree species, Scots pine and Norway spruce have almost equal volume share with minor prevalence of the second one (by 4%). Group of hardwood broadleaves was absent and group of softwood broadleaves was only represented by birch. This situation is more or less common for geographic region of Stockholm.

It was an important element in productivity analysis to consider the distribution of standing stocks in studied forests by age groups (young, mid-aged, premature, mature and overmature; Normative and reference materials for forest mensuration in Ukraine and Moldavia, 1987; Appendix 5) and groups of forest-forming tree species (table 3.4).

Table 3.4 Distributionofforests' standing stocks by age groups, % .

Object	Conifers				Hardwood broadleaves				Softwood broadleaves			
	young	mid-aged	premature	mature and overmature	young	mid-aged	premature	mature and overmature	young	mid-aged	premature	mature and overmature
Kyiv sample	2,7	82,1	3,5	11,7	5,5	58,2	24,2	12,1	2,5	58,9	17,2	21,4
Stockholm sample	7,1	3,9	9,4	79,6	0,0	0,0	0,0	0,0	0,7	24,2	23,1	60,6

After analysis of information in table 3.4 it becomes obvious that age structure of standing stocks of studied forests was very different. Distribution of standing stocks of studied forests by age groups was uneven with considerable predominance of one age group. In case of Communal enterprise "Darnytsya forest-park economy" prevailing stands were mid-aged ones, while in Huddinge forests mature and overmature stands dominated. This type of age distribution in studied urban forests of Kyiv indicates that their protective functions are performed efficiently, since biomass production processes are more intense in younger stands (Gower, McMurtie, Murty, 1996). Though, this situation will require improvement of age structure and replacement of aging stands urgent in nearest future.

Predominance of mature and overmature stands in Huddinge forests has a negative effect upon the potential carbon-sequestering and oxygen producing functions as well as ecological stability. Though, it is undeniable that older stands are more favorable from aesthetic viewpoint. In this situation improvement of age structure and intensified forest protection may be recommended.

For better understanding of the data from table 3.4, let us show graphically stock percentages of age groups in the studied forests (Figure 4).

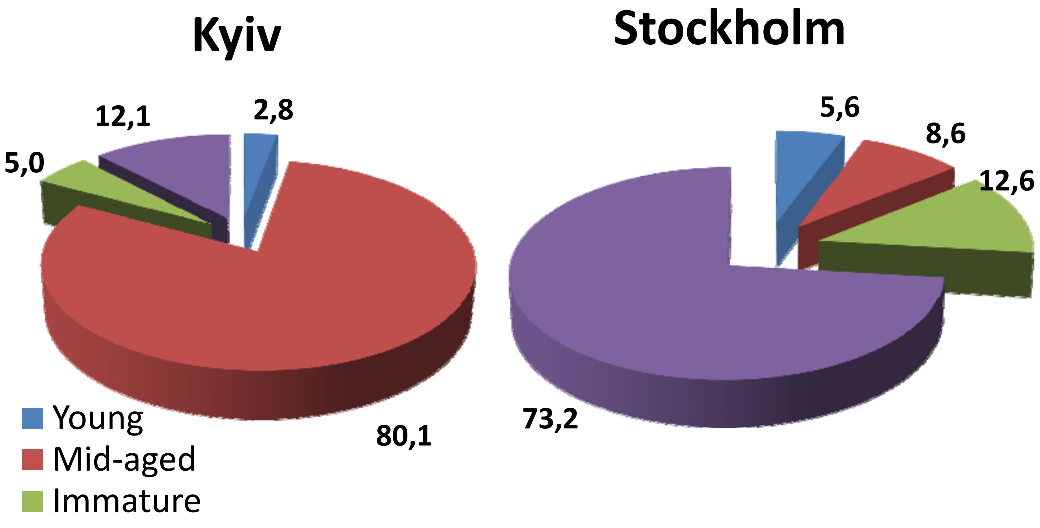

Figure 4. Stock percentages of age groups

Site index class of a stand is a measure of its productivity. By examining average site index classes it becomes possible to characterize productivity of large forest areas. Information on average site indices of studied forests was given and analyzed as another characteristic of sample data (table 3.5).

Table 3.5 Average site index classes (by M.M. Orlov).

Object	Average site index		
	conifers	hardwood broadleaves	softwood broadleaves
Kyiv sample	I^a,1	I,5	I,2
Stockholm sample	III,7	–	I,2

Based on the information in table 3.5, it is possible to say that average site index classes of groups of forest-forming species of Communal enterprise "Darnytsya forest-park economy" (Kyiv sample) are higher or equal than those of corresponding groups of forest-forming species of forests of the Stockholm sample. This means that biomass production in Ukrainian forests is higher. It is obvious, after characterizing sample data, that studied forests of both sample areas, taking into account climatic conditions and geographic position, were highly productive. Oxygen productivity as well as other ecological functions, related to bioproductivity of forest stands, is affected by stand age. Information on mean age of studied forests with respect to groups of forest-forming tree species is provided in table 3.6.

Table 3.6 Mean age of groups of forest-forming species of assessed forests.

Object	Group of forest-forming species	Mean age, years
Kyiv sample	–	75
	Coniferous	74
	Hard-leaved broadleaves	97
	Soft-leaved broadleaves	45
Stockholm sample	–	80
	Coniferous	85
	Hard-leaved broadleaves	–
	Soft-leaved broadleaves	65

By analyzing the information from table 3.6 it is possible to conclude that in general studied pre-urban forests of Stockholm sample area are older than studied urban forests of Kyiv sample area. Since the studied forests are not young, older age implies lower intensity of bioproductivity processes (see comments to table 3.4). This together with natural factors may lead to lower oxygen productivity and carbon sequestration in studied pre-urban forests of Stockholm sample area.

4. Results

The result of applying all the operations to the dataset specified in Materials and Methods was the amount of phytomass in bone-dry state and carbon sequestered in the phytomass. Information on total amount of phytomass was given by groups of forest-forming species and by phytomass fractions. Information on amount of deposited carbon is given by the groups of forest-forming species only.

The CARBON programme was able to calculate density of the abovementioned characteristics. Densities of phytomass and deposited carbon had very high importance. Using these densities it becomes possible to assess the intensity of biomass production process and to compare the two objects of research. The information on total amounts of phytomass and deposited carbon of the examined Swedish and Ukrainian forests is provided in table 4.1.

Oxygen productivity of the forests assessed was calculated after output results of CARBON programme became available. The basis for calculating oxygen productivity consists of the basic provisions of Tshesnokov and Dolgosheev technique (see chapter 3) and the table of average ages of groups of forest-forming species (see table 3.6).

The results on oxygen productivity are given by the groups of forest-forming species. In order to provide a possibility of comparison of the results for the two objects of research, overall production of oxygen was re-calculated in tons per year and square meter of forested land.

Table 4.1 Phytomassand deposited carbon of assessed forests.

Object	Group of forest-forming species	Forested land, 10^3 of ha	Standing stock,$10^6$of m^3	Phytomass components, 10^6 of tons						Phytomass density, kg·m^{-2}	Carbon	
				leaves (needles)	branch wood and bark	stem wood and bark	roots	understorey vegetation	total		total, 10^6 of tons	density, kg·m^{-2}
Kyiv sample	**TOTAL**	**15,3**	**5,4**	**0,060**	**0,239**	**2,405**	**0,521**	**0,150**	**3,376**	**22,1**	**1,677**	**11**
	including:											
	Coniferous			0,055	0,201	2,145	0,453	0,143	2,997	22,6	1,489	11,2
	Hard-leaved broadleaves			0,003	0,026	0,165	0,042	0,003	0,240	24,4	0,120	12,1
	Soft-leaved broadleaves			0,003	0,011	0,095	0,027	0,004	0,139	13,4	0,069	6,7
Stockholm sample	**TOTAL**	**3,4**	**0,5**	**0,008**	**0,018**	**0,222**	**0,043**	**0,007**	**0,297**	**8,7**	**0,148**	**4,4**
	including:											
	Coniferous			0,007	0,012	0,162	0,030	0,005	0,215	8,4	0,107	4,2
	Hard-leaved broadleaves			0,000	0,000	0,000	0,000	0,000	0,000	0	0,000	0
	Soft-leaved broadleaves			0,001	0,006	0,059	0,014	0,002	0,082	10,3	0,041	5,1

The results of oxygen productivity calculation are shown in table 4.2.

Table 4.2 Overall oxygen productivity.

Object	Group of forest-forming species	Overall oxygen productivity, tons per year
Kyiv sample	TOTAL	61884
	Coniferous	55667
	Hard-leaved broadleaves	3413
	Soft-leaved broadleaves	4244
Stockholm sample	TOTAL	5058
	Coniferous	3434
	Hard-leaved broadleaves	–
	Soft-leaved broadleaves	1734

The overall lproduction of oxygen in tons per year and square meter of forested land equals to 0,4 kg m^{-2} for Kyiv sample area (Communal enterprise “Darnytsya forest-park economy”) and 0,2 kg m^{-2} for Stockholm sample area (the assessed part of the forests in Huddinge).

5. Discussion

The result of the master thesis project is comprised by estimates of carbon-sequestering and oxygen-producing functions of a part of urban forests of Kyiv and of a part of pre-urban forests of Stockholm. Performed work had some practical issues, which are connected with data processing. Derived results have practical and scientific importance.

During the period of gathering and processing of initial data few difficulties emerged. Fortunately, all of them were possible to overcome more or less successfully. The first complication was connected with absence of information on top heights of stands in Huddinge dataset. It turned out that site index, stand age and top height are correlated, so by knowing two of them; it was possible to derive the third one.

Top heights for stands of all species in Swedish dataset were calculated using the SI computer programme. It is worth mentioning that the abovementioned programme gives adequate results within the limited range of stand age. When Stand age is outside that range, reliability of the result becomes low and a so called “extrapolation problem” occurs. This shortcoming became evident when calculations of top heights of birch stands in rich conditions were performed. In this case, at the age of +120 years, top height was, 40-43 meters, according to SI programme.

The similar difficulty arose when average heights of stands were calculated by stand age and top height, using the regression models mentioned in chapter 3. The calculated average height was in this case bigger than the top height of the respective stand. The worst in this respect was the regression model for Norway spruce (eqn. 1), where already at age of 110 years calculated average heights were unreliable. It is worth mentioning that models for pine and birch worked much better and no loss in reliability of results was observed, thus there was no need of making any corrections.

The “extrapolation problem” was solved by setting the constant average height or by setting a constant multiplier for top height after the certain age. This operation gave a possibility to use Swedish dataset without need of excluding some of the stands. The disadvantage of this method was reduced (but not much) accuracy of predicted average heights for old Norway spruce stands. This approach also distorts the true variability of top heights and average heights of stands.

The next “compatibility problem” appeared when parameters of phytomass and deposited carbon were calculated by the CARBON programme. The pith of the matter was the following: although group of hard-leaved broadleaf forest-forming tree species was absent in Swedish dataset, the resulting table of CARBON programme included information about phytomass fraction of roots for this group. This resulted in wrong calculation of phytomass density and density of deposited carbon. The way out was quite simple and the abovementioned densities were calculated manually for Swedish dataset.

The comparison of the results between datasets became possible owing to flexibility of methodology of processing sample data and calculating final results. Nevertheless, existing regression models and programmes can be improved. The models can be enhanced by widening the range of input data (ages of stands), used for determining coefficients of these models. Improvement of existing programmes (SI, CARBON), to my opinion, shall be done by increasing amount of testing, validation and internal error correction, especially using extreme combinations of input data. Another thought is to use age classes instead of age groups for input data aggregation and further calculations. Firstly, this option will make the software more flexible by diminution of dependency of results from applied maturity age. Secondly, it would increase the accuracy of results, even though more operations on data aggregation will be needed.

The most correct way regarding the research methodology and purity of experiment would be sampling information from forest sample plots in Sweden, gathering and processing research material with the aim of identifying values of conversion coefficients Rv for Swedish natural conditions. The next step would be substitution of identified Rv values to the equation (5) and calculate different phytomass fractions. The same could be done about estimation of oxygen productivity if it was calculated from yield tables of biomass components in modal stands. This method would be more accurate, but it would also require much bigger amount of field work and data processing.

Tables 4.2 and 4.3 show in this study that the amounts of accumulated phytomass, deposited carbon and oxygen productivity in forests of Communal enterprise "Darnytsya forest-park economy" are substantially higher than the pre-urban forests of Stockholm. If we take into consideration not only the absolute values of abovementioned indices, but also their densities, it becomes evident that biomass production of examined Ukrainian forests is higher than of studied Swedish forests. As a result of that, carbon-sequestering and oxygen-producing functions are performed more efficiently in urban forests of Kyiv city. Literally, in terms of carbon density the difference is 250%, and in terms of oxygen productivity per unit area the difference is 200%. There are several factors which help to explain this phenomenon.

When analyzing the phenomenon described above, one has to keep in mind the way the results were obtained. Amounts of sequestered carbon and produced oxygen were calculated based on assessment of live biomass of the studied forests:

$$\mathbf{LB_{stand} = \Sigma M_{fr},}$$

and

$$\mathbf{M_{fr} = GS \cdot R_{fr},}$$

where $\mathbf{M_{fr}}$ – mass of live biomass fractions in bone dry state,
GS – growing stock,
$\mathbf{R_{fr}}$ – conversion ratio for live biomass fractions.

In terms of growing stock, there is a huge difference between the two study objects, and the main reason for that are their areas. Therefore, it is worthwhile to draw attention to growing stock per unit area. This parameter differs 240% (353 $m^3 \cdot ha^{-1}$ for studied part of urban forests of Kyiv and 147 $m^3 \cdot ha^{-1}$ for studied part of pre-urban forests of Stockholm), and this largely explains the difference in final values of assessed parameters. There is one more driving force – wood base density. But, since it is included in the technique and mathematical models of $\mathbf{R_{fr}}$

– conversion ratios for live biomass fractions – are constant, wood base density could not influence the result in this assessment.

Therefore, it is necessary to look into difference in growing stock per unit area and distinguish drivers, which could lead to big disparity of this index for the two study objects. One likely explanation is the difference in forest growing conditions. Among those, the following are the primary priority to look into:

- Water availability. The precipitation regime is slightly better in areas around Kyiv (70-100 mm annually more than around Stockholm). Nevertheless, water availability is not a limiting factor in neither of the two study objects.
- Nutrient availability. This difference becomes evident when site classes after M.M. Orlov were analyzed in Materials and Methods. Based on these factors it is possible to say that soil fertility and availability of nutrients in the territory close to Kyiv give better conditions for growing highly productive coniferous stands.
- Amount of photosynthetic active radiation per unit area. This index depends on geographical latitude of the studied locations. Since Stockholm area is located farther from Equator, amount of photosynthetic active radiation per unit area there is lower, therefore less can be utilized for photosynthesis.
- Growing season length. This parameter is more favorable in areas around Kyiv as well.

As it is possible to see from the facts above, in majority of cases forest growing conditions are less favorable in areas around Stockholm.

The next reason for observed difference is silvicultural practice. It is worthwhile to take into consideration the following conditions:

- Species composition. In general, situation with species composition in better in studied part of pre-urban forests of Stockholm, where bigger amount of mixed stands is present than in studied part of urban forests of Kyiv. Although absence of hard-leaved broadleaf species (like oak, beech, hornbeam etc.) in the studied part of pre-urban forests of Stockholm city may happen to be another reason for their inferior bioproductivity, this fact could not majorly influence the final result. Wood base density is usually higher in stands of hard-leaved broadleaf group of forest-forming tree species and this is explained by biological peculiarities influencing wood structure of those species (The Encyclopedia of Wood, 2007; Panshin, de Zeeuw, 1980; Fukazawa, 1984), but this parameter is constant in this research due to applied system of bioproductivity models. Growing conditions for abovementioned species can be too harsh in Huddinge as well.

- Planting schemes and density. It is known (Razin, Rogozin, 2009) that stands with higher initial density in their natural development reach maximum of their mensurational parameters sooner and retain that maximum for shorter amount of time than stands with lower initial density. Nevertheless, since stands of both study objects are treated, it is not clear for comparison how exactly the treatment applied influences growing stock development.
- Thinning regimes and relative stocking. This factor may influence growing stock and total production development significantly (Nilsson, Agestam, Ekö et al., 2010). Thinning regimes vary from stand to stand in both study objects, therefore it is hard to distinguish in which of them the conditions are more favorable.
- Maturity age and age structure. It is well known that mature and overmature stands are inferior to mid-aged ones in terms of bioproductional processes intensity. Prevalence of mature and overmature stands in the studied part of pre-urban forests of Stockholm city lowers efficiency of their carbon-sequestering and oxygen-producing functions.

Thereby, the difference in efficiency of carbon-sequestering and oxygen-producing functions can for the most part be explained by differences in forest growing conditions and, to smaller extent, by distinctions of forestry practices.

Following recommendations for improved forest practices can be given for the studied part of urban forests of Kyiv:

- to improve age structure by increasing areas of young stands;

- to provide replacement of aging stands with young ones in time;
- to perform intermediate cuttings and to remove diseased trees in time.

It is possible to recommend the following in order to improve performance of bioproductivity connected ecological functions in the studied part of pre-urban forests of Stockholm:

- to improve age structure by reducing amount of overmature stands;
- to strengthen the protection of stands against forest fires, pests, diseases and other sorts of damaging factors, this is especially actual for overmature stands due to their reduced ecological stability.

There are some common recommendations for both study objects:

- to perform intermediate cuttings and to remove diseased trees in time;
- to equip territories of urban and pre-urban forests with services and utilities in order to diminish anthropogenic load on forest ecosystems.

6. Conclusions

Geographical position of Sweden and Ukraine as central countries of their regions, with developed social and industrial infrastructures commits their science institutions to participate in solving continental and global ecological problems. This kind of problems is represented by questions of carbon sequestering capacity and oxygen productivity of forests. Forests are the dominant element of land flora; it fixes carbon from the atmosphere and sequesters it into phytomass and mortmass.

Global climate change is caused by elevated concentrations of carbon dioxide in the atmosphere and by greenhouse gases. Thus, detailed studies of carbon balance in forest ecosystems are needed. Problems of global ecology cannot be solved satisfactory without assessing the potential role of forests in carbon deposition, quantitative describing and modeling the main fluxes. Data on carbon stock and sequestration assessment are valuable from the “carbon capacity” of forest territories viewpoint, as information on potential object of localization of carbon emissions.

Practical importance of this study is revealed in enhanced testing of methodologies of assessing carbon-sequestering and oxygen-producing functions of forests. Importance of derived results is to deduce differences in forestry practices and their possible consequences.

An important condition for conducting similar studies is the comparability of site conditions of studied forest stands. If this is not taken into account, the results may differ too much to have correct interpretation of possible reasons for differences, since they contain too much uncertainty. Too big differences of results for different sites and objects may increase complexity of their analysis and substantiation dramatically.

From this study it is possible to conclude the following:

1. Studied urban forests of Kyiv city and pre-urban forests of Stockholm city are highly productive for their spatial placing and growth conditions. Their

verdurous mass and bioproductivity increase annually, thus, ecological situation is being improved.

2. Age structure of studied forests is not optimal: mature and overmature stands make up the majority, while young stands are lacking. This leads to increase of average age of forests, worsening of their sanitary conditions and creates disadvantageous conditions for further forestry activities.
3. Studies forests of Kyiv are more efficient in performing carbon-sequestering and oxygen-producing functions than onesof Stockholm (in terms of phytomass and carbon density, and overall production of oxygen). This may be explained by difference forest growing conditions and forestry practices.
4. The applied methodology of assessing carbon-sequestering and oxygen-producing functions is rather flexible, while existing drawbacks may be easily solved.

Despite of existence of some shortcomings, functioning of the applied methodology is deemed to be good. Overall condition of studied forests in terms of their carbon-sequestering and oxygen-producing functions is acknowledged as satisfactory.

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Appendix 1

Glossary. List of terms and definitions used in thesis.

Biomass production – feature of groups or single individuals of live organisms to create, transform and accumulate organic matter in ecosystems. A measure of bioproductivity for terrestrial ecosystems is biotic production of dry organic matter or energy, which is created on unit of area per unit of time. Primary and secondary production is distinguished. Production of autotrophic organisms capable of photo- or chemosynthesis is called primary, and this kind of organisms is called producers. Main role in creating primary production belongs to green plants. Production of heterotrophic organisms is referred to as secondary, and these organisms are called consumers. Comparative evaluation of ecosystems' bioproductivity is given in terms of primary production.

Ecosystem – is an integrated nature complex, which has been forming during a long period of time by living organisms and environment of their existence, where all the components are tightly coupled by matter and energy circulation. Only those environments can be regarded as ecosystems, for which stability, clear internal matter circulation and metabolic energy processes are characteristic (Apostolyuket al., 2001; Odum, 2004).

Ukrainian encyclopedia of forestry (2007) gives the following definition for *stand productivity:* it is a totality of stocks of stands in volumetric or weight units per unit of area per unit of time. Practically, when assessing stands' productivity, only stemwood volume is investigated, disregarding tree crowns, roots, layers of bushes and grass vegetation, and vegetation outside stand layers. Stand productivity is influenced by site conditions, tree species and their origin, stand composition, structure, form, age and density as well as by practically applied stand treatment.

Actual and potential forest productivity is distinguished. *Actual productivity* is characterized by factual production, which is created by an existing stand. *Potential production* means a highest possible stand productivity, which is attained when forest-growing potential is used maximally. Actual productivity is determined by current level of forest management; potential productivity shows possible production, which can be attained when site conditions and results of stand treatment are fully utilized by forest stands.

Complex, arboreous, ecologic, biotic and by-use productivities are marked out (Myakushko, 1972). *Complex productivity* unifies arboreous, ecologic and by-use productivities.

Arboreous productivity means the highest possible acquisition of high-quality timber from unit of area. The impartial indices of arboreous productivity are bonity class and forest type.

Ecologic productivity – is an estimate of environment-creating role of forests, their protective properties, recreational and other resources.

Bioproductivity – is a production, which is being created in aboveground and belowground parts of forest biocoenosis in photosynthesis during unit of time on unit of area. Forest bioproductivity is composed by phytomass, mortmass and production (Bazilevich, 1993). Bioproductivity is characterized by formation of phytomass by plants during photosynthesis process.

Phytomass – is a total mass of live organic matter in aboveground and belowground parts of stand, which is measured in tons of dry organic matter per hectare of area. Phytomass consists of stem wood and bark, branch wood and bark, green assimilating organs, generative organs and root systems. Accumulation of phytomass is influenced by zonal regularities, which depend on edaphic factors within borders of zones.

Mortmass (detritus) – is a total mass of dead vegetable organic matter including dead standing trees, dead branches in a tree crown, tree waste, litter and dead belowground organs.

Production – is an organic vegetable matter, annually created during photosynthesis process. It is divided on green assimilating organs, stemwood, stem bark, branchwood, branch bark, generative organs and belowground root systems.

Net primary production – is an amount of vegetable organic matter, created annually; gross production (total photosynthesis) minus energy losses on autotrophic respiration; or an amount of carbon, transferred to phytomass (Bazilevich, 1993). It is measured in tons per hectare per year of bone dry matter or carbon.

Net ecosystem production is estimated as difference between net primary production and heterotrophic respiration.

Aboveground phytomass of woody plants – is a total mass of components of aboveground part of a tree, namely stem wood and bark, branch wood and bark, leaves (needles), generative organs and fruits.

Belowground phytomass of a tree – is a total mass of a stump and root system components.

Understoreyphytomass – is a total mass of undergrowth, understory (underwood) and live surface cover (including their root systems).

Stem phytomass – is a mass of one central stem of a tree over bark (it is important for broadleaved species, where splittings and epicormic branches are found).

*Crown phytomass*consists of total mass of all the live crown branches together with leaves (needles) and generative organs, including splittings, epicormic branches etc.

Tree greenery (according to State standard of former USSR, which is in force in Ukraine (GOST 21769-84, 1984) – are small crown sprouts, covered with leaves (needles) with base diameter for different tree species below 10 mm. Tree greenery as phytomass component includes fractions of leaves (needles), small branches, generative organs and fruits.

Small branches – are non-lignified or partly lignified crown sprouts with diameter below 10 mm.

Live branches – all branches of tree crown, on which photosynthetic organs produce.

Dead branches – dry branches, boughs, which are located in tree crown, on which photosynthetic organs do not produce.

Content of bone-dry matter – is a relation of mass of a sample in bone dry state to its mass in newly cut state.

Taking into consideration specificity of the study, it is considered necessary to provide definitions, connected with carbon budget.

Deposition – shows quantitative change of carbon stocks excluding: stocks, which are withdrawn during forestry activities, stocks of dead trees, and alienated after forest fires and disturbances organic matter. Measured in tons of carbon and quantities, derived from tons.

Destruction – decomposition of tissues of live plants under the impact of parasites; decomposition of vegetable and other organic remnants in the course of destructors' vital activity. Destruction velocity is expressed by loss of different fractions of vegetable material mass during a period of time and by their half-life period.

Carbon stock – is an amount of carbon present in forest ecosystem in any single point of time.

Carbon sink – is absorption of carbon from the atmosphere by large territorial units of land and ocean.

Carbon emission – is an integral reverse gas flow of carbon from land surface to the atmosphere, measured in tons of carbon.

Appendix 2

Characteristics of individual parameters of forest fund of studied part of urban forests of Kyiv city (Communal enterprise “Darnytsya forest-park economy”).

Table 1. Distribution of forested land area and stock by groups of forest-forming species.

Year of inventory	Percent of forest cover	Area, ha/Stock, 10^3 m^3/Stock percentage			
		total	by groups of forest-forming species		
			coniferous	hardwood broadleaves	softwood broadleaves
1999	24,5	15266,3	13244,9	983,5	1037,9
		5444,0	4977,0	277,7	198,3
		100,0	91,4	5,1	3,5
Average stock, m^3 per ha		357	376	282	182

Table 2. Percentages of stock of main forest-forming species with in the groups of forest-forming species.

Year of inventory	Stock percentage									
	coniferous			hardwood broadleaves			softwood broadleaves			
	pine	spruce	other	oak	beech	other	birch	aspen	alder	other
1999	99,7	0,3	0,0	95,8	0,1	4,1	57,7	4,5	25,1	12,7

Table 3. Distribution of stocks of stands with in groups of forest-forming species by age groups.

Year of inventory	Coniferous				Hardwood broadleaves				Softwood broadleaves			
	young	mid-aged	premature	mature and overmature	young	mid-aged	premature	mature and overmature	young	mid-aged	premature	mature and overmature
1999	2,7	82,1	3,5	11,7	5,5	58,2	24,2	12,1	2,5	58,9	17,2	21,4

Table 4. Average site index classes by M.M. Orlov by groups of forest-forming species.

Year of inventory	Average site index class by M.M. Orlov		
	coniferous	hardwood broadleaves	softwood broadleaves
1999	I^a,1	I,5	I,2

Appendix 3

Characteristics of individual parameters of forest fund of studied part of pre-urban forests of Stockholm city (Huddinge).

Table 1. Distribution of forested land area and stock by groups of forest-forming species.

Year of inventory	Percent of forest cover	Area, ha/Stock, 10^3 m^3/Stock percentage			
		total	by groups of forest-forming species		
			coniferous	hardwood broadleaves	softwood broadleaves
2000	–	3354,6	2560,0	0	794,6
		466,8	358,2	0	108,6
		100,0	76,7	0	23,3
Average stock, m^3 per ha		139	140	0	137

Table 2. Percentages of stock of main forest-forming species within the groups of forest-forming species.

Year of inventory	Stock percentage									
	coniferous			hardwood broadleaves			softwood broadleaves			
	pine	spruce	other	oak	beech	other	birch	aspen	alder	other
2000	48,0	52,0	0	0	0	0	100	0	0	0

Table 3. Distribution of stocks of stands within groups of forest-forming species by age groups.

Year of inventory	Coniferous				Hardwood broadleaves				Softwood broadleaves			
	young	mid-aged	premature	mature and overmature	young	mid-aged	premature	mature and overmature	young	mid-aged	premature	mature and overmature
2000	7,1	3,9	9,4	79,6	0	0	0	0	0,6	22,3	21,3	55,8

Table 4. Average site index classes by M.M. Orlov by groups of forest-forming species.

Year of inventory	AveragesiteindexclassbyM.M. Orlov		
	coniferous	hardwood broadleaves	softwood broadleaves
2000	III,7	–	I,2

Appendix 4

Parameters of equations used in this study, for estimation of conversion coefficients for phytomass fractions in stands of main forest-forming species of Ukraine.

*Rv*ratio	Number of cases	Equation type	Equation number	Equation parameters				Q
				b_0	b_1	b_2	b_3	
Pine								
Rv(f)	193	I	1,1	5,715	-1,602	-1,170	0,011	0,9
Rv(br)	172	I	1,2	4,703	-1,013	-1,272	0,007	0,85
Rv(st)	193	I	1,3	-1,346	0,071	0,021	0,003	0,98
Rv(bl)	66	I	1,4	1,601	-0,218	-1,08	0,009	0,57
Rv(us)	20	I	1,5	5,383	-1,726	-0,999	0,023	0,68
Spruce								
Rv(f)	41	I	2,1	9,123	-2,931	-0,840	0,034	0,96
Rv(br)	41	I	2,2	6,696	-2,172	-0,779	0,026	0,88
Rv(st)	41	I	2,3	-0,696	-0,165	-0,010	0,006	0,92
Rv(bl)	15	I	2,4	5,107	-1,890	-0,483	0,025	0,49
Rv(us)	14	I	2,5	13,004	-1,940	-3,398	0,020	0,82
Oak								
Rv(f)	41	I	3,1	3,766	-1,157	-1,062	0,002	0,83
Rv(br)	41	I	3,2	1,285	-0,143	-0,805	-0,004	0,44
Rv(st)	41	I	3,3	-0,975	-0,045	0,144	0,002	0,25
Rv(bl)	18	I	3,4	-7,271	-1,131	2,643	0,015	0,92
Rv(us)	8	I	3,5	-7,759	4,137	-2,910	-0,058	0,80
Birch								
Rv(f)	9	II	5,1	7,108	-0,826	-2,332	-	0,75
Rv(br)	9	II	5,2	5,309	-0,773	-1,464	-	0,85
Rv(st)	9	II	5,3	-0,634	0,028	-0,023	-	0,83
Rv(bl)	8	II	5,4	0,187	-0,330	-0,272	-	0,98
Rv(us)	8	I	5,5	6,030	0,116	-2,610	-0,025	0,78

Aspen								
Rv(f)	24	II	6,1	4,056	-0,95	-1,556	-	0,84
Rv(br)	24	II	6,2	1,978	-0,339	-1,19	-	0,63
Rv(st)	24	II	6,3	-0,11	-0,040	-0,214	-	0,23
Rv(bl)	3	III	6,4	1,009	-0,785	-	-	0,71
Rv(us)	4	III	6,5	-0,350	-1,131	-	-	0,74
Alder								
Rv(f)	13	II	7,1	0,655	-0,750	-0,749	-	0,74
Rv(br)	13	II	7,2	-2,045	0,291	0,032	-	0,58
Rv(st)	13	I	7,3	-1,686	0,243	0,084	-0,005	0,48
Rv(bl)	8	II	7,4	-0,730	-0,020	-0,393	-	0,45

Appendix 5

Distribution of forest stands by age groups depending on final felling age and length of age class (Normative and reference materials for forest mensuration in Ukraine and Moldavia, 1987).

Forest-forming tree species	Age of final felling, years	Length of age class, years	Age classes				
			of young stands	of mid-aged stands	of immature stands	of mature stands	of overmature stands
Conifers and high growth hardwood broadleaves	101-120	20	I-II	III-IV	V	VI-VII	VIII+
	81-100	20	I-II	III	IV	V-VI	VII+
	111-120	10	I-IV	V-IX	X-XI	XII-XV	XVI+
	101-110	10	I-IV	V-VIII	IX-X	XI-XIV	XV+
	91-100	10	I-IV	V-VII	VIII-IX	X-XIII	XIV+
	81-90	10	I-IV	V-VI	VII-VIII	IX-XII	XIII+
	71-80	10	I-IV	V	VI-VII	VIII-XI	XII+
	61-70	10	I-II	III-IV	V-VI	VII-X	XI+
Softwood broadleaves and low growth hardwood broadleaves	61-70	10	I-II	III-V	VI	VII-VIII	IX+
	51-60	10	I-II	III-IV	V	VI-VII	VIII+
	41-50	10	I-II	III	IV	V-VI	VII+
	31-40	10	I	I	III	IV-V	VI+
Fast-growing softwood broadleaves	26-30	5	I-II	III-IV	V	VI-VII	VIII+
	21-25	5	I-II	III	IV	V-VI	VII+
	16-20	5	I	II	III	IV-V	VI+