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The monograph outlines the views of Belarusian experts on the contribution of the forest sector of Belarus to mitigation of weather and climate impacts on the environment which is made through carbon dioxide absorption by forests and partial sequestration of carbon in the forest fund components. It touches upon the calculation of carbon dioxide emissions and absorption, the carbon budget of the Belarusian forest fund, relationship between the age and species structure and the carbon dioxide absorption by forests, measures on increasing of carbon dioxide absorption by forests, etc.

The monograph is intended for a wide range of professionals engaged in forestry, environment, economy, nature management as well as for teaching professionals, PhD students, graduate and undergraduate students doing their degree in forestry and biology, etc.

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1

PREFACE AND GENERAL PROVISIONS

Among all global environmental concerns climate change has the most prominent impacts on sustainable development of human civilization. The last quarter of XX century and the current years of XXI century were characterized by sudden warming. This process is largely influenced by changing atmospheric composition and considerable increase in greenhouse gases amount.

Reduction of the greenhouse gases amount in the atmosphere is particularly important to mitigate climate change impacts. Restoration of the forest areas can be a viable solution to the problem. Unfortunately, the total forest area has decreased by 3% since 1995 until now. The World Bank promotes climate change mitigation through Small Grants Program of the Global Environment Facility. The actions include forest cuts, expanded forest growing, forest regeneration as well as larger contribution of forests to sustainable development.

The Belarusian Forestry Development Project (2015) is a good example of long-standing strategic cooperation between the World Bank, the Global Environment Facility and the government of the Republic of Belarus. The Republic of Belarus is one of the most forested countries in Europe and Central Asia. This project is a second one for the forest sector of the Republic of Belarus funded by the World Bank.

The first forestry development project implemented from 1994 to 2002 was the first investment project of the World Bank in Belarus. The funding provided by the World Bank made the following actions possible: introduction of the information system of forest management, monitoring system for forests, contaminated and swampy lands, purchase of the cutting-edge machinery for forest growing and timber harvesting, equipping of the forest seed-selection centre, implementation of educational programs at Belarusian State Technological University and industry-specific educational centre, improvement of material facilities of forestry research and education institutions.

One of the vital elements of the project was the Strategic Forestry Development Plan for Belarus for 1997–2015. Historically, the most important document of strategic planning was the General Forestry Development Plan for the Byelorussian Soviet Socialist Republic. The document was made in 1959 and remained effective until 1975, so it envisaged the conditions and rates of forestry development for 17 years. The Strategic Forestry Development Plan adopted in 1997 was different from the preceding program documents as it embraced a large scope of forestry issues. It also outlined such issues as improvement of ownership forms and management, solutions to economic problems, development of forestry education and research, technical improvement of the industry and implementation of advanced forestry technologies, staff optimization, new forest policy and laws. Special emphasis was placed on forest ecology as a basis for stabilization of the human environment and habitats for other species in view of their contamination, forest drying-out, forest fires, pests and diseases and other harmful anthropogenic impacts on the forest ecosystem of Belarus.

Later, the regional program "European Neighborhood and Partnership Instrument Forest Law Enforcement and Governance – ENPI FLEG-2" was implemented in Belarus. The Program involved the development of the Strategic Forestry Development Plan for 2015-2030. The Plan was approved by M.I. Rusyi the Deputy Prime Minister of the Republic of Belarus on December 23, 2014 (No. 06/201-171) and is fully consistent with the provisions of the new Forest Code (2016). The actions of the Plan can be regarded as new tasks and approaches to forest management in Belarus.

The goals of the Belarusian Forestry Development Project include improved efficiency of forest management, forest regeneration and forest growing, enhanced use of logging residues and increased contribution of forests to human welfare in targeted forest areas of the Loaner.

This collective monograph resulted from the task "Prepare a National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030" done under Contract № BFDP/GEF/CQS/16/25-26/17 dated October 23, 2017 between the Ministry of Forestry of the Republic of Belarus and Belarusian State Technological University. The task was a part of the Belarusian Forestry Development Project TF0A1173 GEF/WORLD BANK. The monograph outlines the views of Belarusian experts on the contribution of the forest sector of Belarus to mitigation of weather and climate impacts on the environment which is made through carbon dioxide absorption by forests and partial sequestration of carbon in the shape of phytomass carbon, organic soil carbon and other forest fund components. The monograph touches upon the following issues: calculation methodology for carbon dioxide emissions and absorption by forest ecosystems; determination of carbon reserves and flows (pools) in the Belarusian forest fund; the carbon budget of the Belarusian forest fund; relationship between the age and species structure and the carbon dioxide absorption by forests; international practices of measures on increasing the level of carbon dioxide absorption by forests; review of the national legislation related to greenhouse gases absorption by sinks (Forests, swamps); measures of the National Action Plan on Increasing the Absorption of Carbon Dioxide by the Belarusian Forest Fund.

The monograph is intended for a wide range of professionals engaged in forestry, environment, economy, nature management as well as for teaching professionals, PhD students, graduate and undergraduate students doing their degree in forestry and biology, etc.

1.1. Introduction

The modern paradigm of the human attitude to forest sees the forest not only as a source of timber and other material resources alone. The habitat-forming function of forests gains in importance along with their special social and environmental functions in providing a healthy living environment on the planet. Recently, industrial carbon dioxide emissions, its enhanced concentration in the atmosphere and possible climate change impacts have become global concerns.

Climate change of the recent decades has been caused by increased concentration of greenhouse gases in the atmosphere. Main greenhouse gases that have destabilizing effect on the atmosphere are carbon dioxide, methane, nitrogen oxide and chlorofluorocarbons. The total amount of greenhouse gases is dominated by carbon dioxide (76%).

The importance of forests in regulation of greenhouse gases content of the atmosphere was adopted as a key issue of international climate change conventions. Absorption of substances by forest vegetation occurs during nutrition process. The nutrition can be divided into carbon or aerial, plant nutrition (photosynthesis), water nutrition (hydrogen and oxygen), nitrogenous and mineral.

Plants take up nitrogen through their roots in the form of mineralized ammonia nitrogen. Specific weight of absorption of nitrogen oxide by plants is inconsiderable as compared to nitrogen fixation of atmospheric molecular nitrogen. Thereby forests have no significant impact on mitigation of the greenhouse effect.

Main biological sink of atmospheric methane is its oxidation in soil. Methane absorption by forest fund is relatively small, i.e., about 0.5 million t in CO_2 equivalent.

Natural absorption of chlorofluorocarbons by Belarusian forests is lower than 4 t per year.

The role of forest and other vegetation communities of the forest fund as greenhouse gases sinks is exercised through carbon dioxide absorption during primary synthesis of organic substances (photosynthesis). In view of this, the measures for forests and swamps contained in this National Action Plan include measures on increasing the level of carbon dioxide absorption by all types of forested lands of the Republic of Belarus.

The biomass of wood and other components of forest ecosystem of the Republic of Belarus has accumulated considerable amount of carbon. Over 1956–2017 (true and fair record period) the carbon content in Belarusian forests increased by more than 2 billion t. This corresponds to the absorption ("removal") of more than 7 billion t CO_2 from the atmosphere if taken as CO_2 equivalent. Experts estimate that CO_2 weight gain ("emission") in the atmosphere amounted to approx. 420 billion t. The Republic of Belarus, whose population makes only 0.15% of the total world population, has compensated 1.83% of the global emissions over the past seven decades. This is 12 times as effective as a per capita contribution by the global forest ecosystem. The current dynamics of carbon flows in the Belarusian forest fund should be given special attention. In particular, annual carbon dioxide absorption by forest fund areas is equal to the compensation of a smaller half of the industrial greenhouse gases emissions in the Republic of Belarus.

High carbon sequestration capacity of the Belarusian forests results from the increased forest cover in the country, enhanced forest productivity, environmentally sound timber harvest and other factors. Under the conditions of global deforestation, decreasing forested areas and wood reserves in the global forest ecosystem, careful consideration and dissemination of the good practices of Belarusian silviculturists in the field of increasing of forest resources and carbon dioxide “stock” by forests are highly recommended.

The carbon budget of the Belarusian forest fund may change. The following estimates have been made until 2050 and the second half of XXI century:

– age structure of forests will change towards a “normal” forest;

– timber harvest volumes may increase;

– the area of old-aged conservation forests will increase, they will approach the biological development age and become sources of carbon dioxide “emission”.

In view of the above factors the annual carbon dioxide absorption by the forest fund can decrease to 20–25 million t CO_2/year (halving in the amount of 2017), This trend of the declined carbon dioxide “stock” is contradictory to the national policy of climate change mitigation. Besides, the Republic Belarus has taken several international commitments related hereto.

The Republic of Belarus is an SFM member, i.e., it has taken commitments for sustainable forest management and sustainable development goals. This particularly relates to target **1.2. The world’s forest carbon stocks are maintained or enhanced** under **Global Forest Goal 1** of the six Global Forest Goals specified by ***the United Nations Strategic Plan for Forests*** for 2017–2030 (UNSPF). By the Presidential Decree no. 375 dated 20.09.2016 the Republic of Belarus adopted ***the Paris Agreement commitments*** to reduce greenhouse gases emissions.

Therefore an important task of the forest sector in relation to maintaining and enhancing carbon stocks n national forests can be stated as given below. The statement can be regarded as ***the Mission of Forestry of the Republic of Belarus*** to further develop ***sustainable forest management***.

“*Carbon emissions from wood harvested by final felling, regeneration and other cuttings shall be compensated by increasing of carbon dioxide absorption through responsible forest management*”.

Responsible forest management must fulfill the following condition:

“*Carbon weight that is sequestered in the annual volume of wood harvest by final felling, regeneration cuttings, conversion and other fellings shall not exceed the annual absorption of carbon dioxide resulting from the target measures on increasing the carbon sequestration capacity of forests and non-forested lands of the forest fund*”.

It is for the above mentioned reasons that the World Bank and the Global Environment Facility have included the task on increasing the level of greenhouse gases absorption and the development of a National Action Plan in ***the Belarusian Forestry Development Project***.

The aim of the task is ***Creation of the Enabling Environment*** when undertaking the Mission of the forest sector in maintaining and enhancing forest carbon stocks in the Republic of Belarus.

The objectives of the tasks were:

– to develop working mechanisms for maintaining the achieved carbon budget values in the forest fund of the Republic of Belarus until 2030;

– to recommend to the forest sector efficient economic and other measures on increasing the annual level of carbon dioxide absorption by forest fund components. This will compensate for 24 million t of carbon dioxide emissions in 2018-2030 due to the planned timber harvest increase from final fellings and other cuts by 22 million m^3 or 41.4% as compared to 2017;

– to prepare a draft National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030 indicating specific measures, their volumes, deadlines for implementation, responsible executors (forest fund holders, State Forestry Production Associations, other parties concerned);

– the strategies, plans, forestry-related and other measures must be scientifically-proven, incorporate advanced international and national practices, take into account the balance of social, ecological and economic interests of the Belarusian society and international commitments of the Republic of Belarus.

The problem of maintaining the level of annual carbon dioxide absorption in the forest fund can be solved by ***increased forest productivity***. The following forestry actions hold a lot of promise:

– creation of forest plantations by closed-root-system seedlings of high selection characteristics;

– reconstruction of low-grade forest stands;

– reducing the cutting cycle for partial cuts by means of conservation of young growth and preliminary assistance to natural reforestation.

The actions are a long-term mechanism for improving the forest productivity.

Extensive actions on ***increasing the average density*** of stands are also highly promising. In the past this action was given little attention by silviculturists, however it can result in large wood increment by means of improved forest regeneration and forest care.

Swampy forests occupy 18.6% of the total area and provide almost a half of the carbon budget in the Belarusian forest fund. It is important to preserve and ***enhance the carbon sequestration function of swampy forests***. Some swampy forests are managed. With increased forest road construction their timber harvesting role can be expanded. Under intensive increment of upland mature forests it is advisable to reduce cuts in swampy forests. The National Action Plan suggests switching from the forest management to conservation regime of swampy forests that can be very efficient in terms of carbon sequestration, conservation and promotion of biodiversity.

The forest sector takes actions to optimize age and species structure of forests. Assessments of the effect of changing age and species structure on the level of carbon dioxide absorption are debatable due to the consensus of ecological and economic interests. Besides it is hard to estimate the scope of weather and climate change impacts on the forest ecosystem of Belarus.

Changes in age structure of forests can be achieved over long (several decades) periods. The ideal age structure of forests, so-called "normal" forest, and associated uniform forest management ensures only ***half the current level of annual carbon dioxide absorption***. For this reason the optimization of the age structure of forests is considered as not very significant.

It is not necessary to amend the existing program of optimizing the species structure of the Belarusian forests. ***Change of the species structure of the Belarusian forests*** in any proportion of species and with regard to the balance of ecological and economic interests ***will not affect*** the level of annual carbon dioxide absorption by forests.

These and other actions on increasing the level of carbon dioxide absorption by the forest fund call for the improvement of ***institutional framework of carbon sequestration*** by forests which is also included in the suggested measures.

Legal framework for forest carbon sequestration capacity and stabilizing effect on climate and weather changes in Belarus is satisfactory. This is reflected in Presidential Decree No. 345 dated 20.09.2016 with the resolution to adopt the Paris Agreement from 22.04.2016 as well as in the State Action Plan for Climate Change Mitigation for 2013–2030 and other documents.

It is required to develop certain regulatory acts for the forest sector, to include:

– obligatory ***carbon flow monitoring*** by means of State Forest Cadastre;

– account for carbon sequestration in ***allowable cuts***;

– more detailed carbon sequestration measures in ***forest inventory projects***;

– ***Guidelines for calculation of carbon dioxide absorption and emissions*** in the forest fund of the Republic of Belarus shall be given a status of a regulatory legal act.

About 94% of the suggested actions on increasing the level of carbon dioxide absorption by the forest fund are to be implemented by the Ministry of Forestry that is the main forest fund owner. However, the actions should be taken by other forest governance bodies as well. Their involvement in the actions on carbon dioxide absorption is expected to increase in the future.

Forests of the Republic of Belarus render important ***ecosystem services*** at the ***European level***. These services include carbon sequestration and ecosystem protection services. Unfortunately there is no legal framework or practices that would provide charges for these services. Measures on carbon dioxide reduction ad absorption by forests do not get sufficient funding by the Belarusian government. Neither are they financially supported by foreign investors. At the same time several countries that have low carbon sequestration capacity of forests have access to free carbon markets of forestry ecosystem services and get investments.

Highly-efficient carbon sequestration activity of the forest sector of Belarus (over the past six decades the forests of Belarus have deposited 7.7 billion t of atmospheric carbon dioxide) deserves attention of ***international investors***. High return on investment in the carbon sequestration services has been demonstrated by the forest sector of Belarus.

Current hardly-predictable and rather negative dynamics of weather and climate impacts on the forest ecosystem puts tremendous stress (large-scale forest drying-out) on the forest sector of Belarus. This can affect sustainable development goals, i.e., seriously change the carbon budget of forests and direct ***the "net flow" of carbon in forests towards the atmosphere***. This change has been in place in the global forest ecosystem due to the "global deforestation" problem.

The implementation of the National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030 developed within the task of GEF/World Bank should be supported by international funds.

The task was jointly performed by leading scientists and forestry professionals:

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1.4. List of main abbreviations, symbols, units of measurement, terms and definitions

UNFCCC: United Nations Framework Convention on Climate Change;
KP: Kyoto Protocol;
IPCC: Intergovernmental Panel on Climate Change;
GG: Greenhouse gases;
t.r.f.: ton of reference fuel;
Belarus NAS – National Academy of Sciences of Belarus;
LULUCF: Land-Use, Land-Use Change and Forestry;
MM: mass media;
NGOs: non-governmental organizations;
RBTS: planting material – root-balled tree system;
SFE: state forest enterprise;
SPFA: State Production Forestry Association;
BSTU: Belarusian State Technological University;
MF: Ministry of Forestry of the Republic of Belarus;
SFR: State Forest Register;
GIS: Geographical Information System;
SFI: State Forest Inventory;
ECE UN FAO: Economic Commission for Europe of United Nations Food and Agriculture Organization;
BGR: biomass growth rate;
REFCB: regional evaluation of forest carbon budget;
USFEU: Ural State Forest Engineering University;
CBM-CFS: Carbon Budget Model of the Canadian Forest Sector;
EFIMOD: Discrete Lattice Ecosystem Simulator;
FCA: Full Carbon Account;
FORCARB2: Budget Model of Local Spatial Level;
IIASA: International Institute for Applied Systems Analysis;

NFC-MARS: National Forest Carbon Monitoring, Accounting and Reporting System;

NPP: Net Primary Production;

EU: European Union;

UN: United Nations Organization;

PA: protected areas;

BAS: biologically active substances;

DR: dust retention;

Z_M^{cur}**:** current stock increment;

Z_M^{av}**:** average stock increment;

F_E**:** factor of ecological efficiency of a stand древостоя;

N_2O – nitrogen oxide;

C: carbon;

CO_2**:** carbon dioxide;

CV: share of carbon (C) in the stand components per one unit of stemwood volume, tC/m^3;

CH_4 – methane;

O_2 – atmospheric oxygen;

ha – hectare;

g – gram;

kg – 10^3 g, kilogram;

Mg – 10^6 g, megagram, ton;

t – ton, 10^6 g, megagram;

Gg – 10^9 g, gigagram, 10^3 t, thousand t;

Tg – 10^{12} g, teragram, 10^6 t, million t;

Pg – 10^{15} g, petagram, 10^9 t, billion t;

P: average density of forest stands;

m^3/ha**:** cubic metre per hectare;

CO_2 **absorption:** absorption of carbon dioxide from atmospheric air, tCO_2;

forest carbon budget: collection of information about the carbon stock and flows in forest fund;

windbreak (windfall, deadfallen wood): tree trunks or their parts that have fallen onto the ground, i.e., dry and rotting branches and limbs; windfallen or snowfallen trees, wood that has been felled but not logged and left in the forest (often considered unusable);

annual absorption of carbon dioxide by forest: accumulation of carbon dioxide fixed in the annual increment of phytomass, dead phytomass and organic soil carbon per one hectare of forest fund. It is defined as a difference between the capacity of atmospheric CO_2 fixation during the photosynthesis of forest vegetation (“total photosynthesis”), on the one hand, and total CO_2 emission as a result of vegetation and soil respiration, wood harvesting (logging), forest fires, forest damage by pests and diseases, burning of logging residues on felling sites, on the other hand, tCO_2/ha/year;

"carbon forests": growing or planted forests withdrawn from economic use for long-term timeframe for carbon sequestration purposes;

growth class: indicator of potential productivity of forest stands;

forest components in carbon flows calculations: overground phytomass, underground phytomass, dead phytomass, organic soil carbon;

forest carbon cycle: ongoing process of mutual carbon absorption of atmospheric carbon by forest vegetation during photosynthesis with the formation of organic substances, partial deposition of carbon in phytomass and soil or its subsequent atmospheric re-entry during vegetation respiration and dead phytomass mineralization in forest;

forest fund: lands allocated to carry out forestry activities

forest lands: lands belonging to forest fund and allocated to forest growing ;

forest cover: share of lands covered with forest in the total area under consideration;

small biological forest cycle: sequence of processes of the entry of soil and atmospheric substances into vegetation, return of life substances into soil and atmosphere and their conversion into the compound substances absorbable by forest vegetation;

dead forest phytomass: total organic substance amount contained in the forest floor, dead standing trees, windfallen trees, dead / fallen branches, roots and stumps forest under storey and forest live cover in the forest lands;

young stands: stands of age classes 1 and 2;

non-forest lands: lands belonging to forest fund but not intended for forest growing;

carbon net flow: carbon exchange between ground ecosystems and atmosphere;

complete stand: a stand having such a structure, species, age and growing conditions to be considered the most perfect-quality (M.M. Orlov), A stand with the relative density of 1.0;

total change of forest-sequestered carbon: difference of total forest carbon between the current and the previous years, tC/year;

organic soil carbon: carbon content in the upper 30-cm layer of sandy, sandy-loam and clay-loam soils all the way down to the peat layer of wet peaty and peat-boggy soils, tC;

Paris Agreement: an agreement adopted at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change on December 12, 2015 in Paris and signed on April 22, 2016;

greenhouse gases: gaseous atmospheric constituents of natural or anthropogenic origin that absorb and re-emit infrared radiation. They are assumed to cause global greenhouse effect;

greenhouse effect: increase in temperature of lower atmosphere layers as compared to the effective temperature, i.e., temperature of planet's heat radiation as detected from space;

overmature stands: stands older than those of the prescribed felling age;

ripening stands: age class preceding the age of mature forest stands;

carbon pool: carbon amount that is fixed by forest or its components during the "sink-emission" process of carbon dioxide, tC or tCO_2 equivalent;

soil carbon sequestration by forests: the process of organic carbon withdrawal from small biological cycle by forests to enable its long-term preservation as humus or peat;

middle-aged stands: forest stands older than young ones and ripening stands (age class 3 of commercial forests, age classes 3 and 4 of other forest categories);

mature stands: age class of stands intended for final yield;

forest maturity: the age of stands with maximum increment of the parameter under study;

average carbon sequestration: carbon amount fixed by one hectare of forest fund or its components (phytomass, dead phytomass, soil, etc.), tC/ha;

average change of carbon sequestration by forest: difference of average carbon sequestration between the current and the previous years, tC/ha/year;

CO_2 sink (absorption): carbon dioxide absorption from the atmosphere during photosynthesis of green plants, including forest vegetation, tCO_2;

total forest carbon: total carbon amount in forest, tC;

current increment: increase of a certain parameter over *n* years with account of loss of growing forest: $Z_{M}^{cur} = M_A - M_{A-n} + O_n$;

forest dead phytomass carbon: carbon content in forest floor, dead-standing trees, windfallen trees, dead / fallen branches, roots and stumps under storey and forest live cover in the forest lands, tC;

CO_2 quota: highly regulated means of payment used to compensate or neutralize CO_2 emissions. One CO_2 quota gives the right to one-ton carbon dioxide emission or equivalent amount of another greenhouse gas;

carbon credit: all types of greenhouse gas emission reduction as a result of project solutions. 1 carbon credit = 1 ton of carbon dioxide emissions;

conditionally-mobile organic carbon in forest: carbon amount in the 0-10-cm soil layer of forest lands;

conditionally-stable organic carbon in forest: carbon amount in the 10-30-cm soil layer of forest lands;

overground phytomass of forest: total amount of live organic vegetative substance accumulated by a stand, young growth and under storey as well as in forest live cover of forest and non-forest lands;

underground phytomass of forest: total amount of live organic vegetative substance accumulated by roots, underground stems, nodules, bulbs, etc. of trees of young growth and under storey as well as forest live cover of forest and non-forest lands.

2

CALCULATION METHODOLOGY FOR CARBON DIOXIDE EMISSIONS AND ABSORPTION BY FOREST ECOSYSTEMS

2.1. Analysis of the existing methods, tools, and technologies for collecting information in order to determine the level of absorption of greenhouse gases by sinks (forests, swamps)

The obligation to achieve the principal goal of the United Nations Framework Convention on Climate Change, i.e. stabilization of the greenhouse gases concentration at the level which would prevent dangerous anthropogenic impact on the climate system served as a prerequisite for applied research into the development of methodology for the record of greenhouse gases emission and absorption by ecosystems, thus allowing the estimation of carbon stock in different pools and its time dynamics.

The most unbiased data can be obtained by direct observations of CO_2 flows and carbon exchange between the atmosphere and the ecosystem for which purpose micrometeorological method of eddy covariance was developed and is being applied. The method is based upon measuring of concentrations and flows of carbon dioxide and other greenhouse gases along the vertical profile of ecosystems [1]. The method requires special-purpose expensive equipment (poles connected to gas analyzers). Reliability of the results obtained can only be achieved after lots of field studies. As has been noted by many experts, the currently accumulated experimental data are not sufficient for regional estimation of carbon exchange and the application of the method does not allow measuring either the carbon content or the level of carbon exchange between the ecosystem and the atmosphere except for particular areas and limited timeframes [2, 3].

Other methods are based upon the balance settlements of carbon flows. In particular, the IPPC methodology involves calculations by five large carbon reservoirs (pools) that include overground phytomass, underground phytomass, dead-standing and windblown wood, forest floor and organic soil substance [4]. It is considered that carbon flow into or out of the atmosphere is equal carbon stock variations in the existing biomass and soil whereas the carbon stock variations are dependent on the transformations in land use and economic activities. After the individual pools have been assessed, the total value of carbon stock ups and downs along the five pools is calculated. Any resulting decrease in carbon stock is converted into CO_2 emission equivalent.

Estimation of the carbon sequestered by phytomass implies identified dependencies between different fractions of woody phytomass. The phytomass stock is assessed using forest inventory data combined with yield tables and regressive dependencies of phytomass on forest taxation indexes. Estimation of carbon sequestration by different components of forest ecosystem is made by means of conversion factors [5-7].

Summary report on forest resources prepared by the Economic Commission for Europe of United Nations Food and Agriculture Organization (ECE UN FAO) [8], subsequently known as IPPC methodology (2003) contains a separate chapter about carbon balance in forests and includes ECE experts' calculations made for Belarusian forests. The points of reference for balance calculations of forest carbon flows by means of ECE UN FAO methodology have been defined as follows:

1. It has been recognized that forest have vast capacity to have a considerable effect on the value and direction of carbon flows in the global carbon cycle. It is particularly noted that today forests fix carbon at the rate of about 60% by vegetation and about 50% by soil.

2. Increasing phytomass in the forest ecosystem results in carbon net flux from the atmosphere to forest and its outflow from the atmosphere thereafter. Decreasing phytomass reverses the net flux direction and results in the atmospheric carbon inflow.

3. Forest statistics has relatively reliable data on wood resources. In certain cases it is possible to obtain data about the stock or weight of roots, branches, vegetative organs, other components (grass-moss-shrub storey, young growth) of forest ecosystem.

4. To calculate the carbon balance it is necessary to convert stock (weight) of stem wood and other phytomass components into dry organic substance together with the determination of their carbon content. ECE UN FAO calculations determine the carbon content in dry phytomass of forest ecosystem as 50%.

5. ECE UN FAO calculations adopt the following ratios to determine dry weight: density of coniferous stem wood is 0.52 t/m^3 (i.e., dry weight of 1 m^3 of wood is 520 kg), density of deciduous wood is 0.66 t/m^3, that of roots incl. stumps is 0.12 t/m^3.

The carbon balance of forests is calculated as described below. As defined by taxation terminology, we should determine the current change in wood resources as a difference between annual increment (net primary productivity) and total annual wood harvest (fellings), natural mortality and other wood losses (dying, fires, etc.). Then other components of a forest stand are estimated by the use of the above ratios, i.e., their dry weight and carbon content.

IPPC Guidelines [4] describe methodology for the estimation of the carbon stock changes in two main carbon pools: biomass and organic soil carbon. They define dead organic substance as a factor that is to be considered during future work by cadastre developing methods. The Marrakesh Accords specify that it is necessary to possess the information about carbon stock changes in five pools: overground biomass, underground biomass, forest floor, windblown trees and organic soil carbon. Reduced stock in one pool must be compensated by increased stock in another pool, e.g., biomass pools are reduced after disturbances, however, the pools of forest floor and windblown trees can be increased at the same time. Thus, changes within one pool can be considerably higher as compared to the resulting changes in the pool aggregate.

After individual pools have been assessed and the relevant data about the pools in a certain area have been communicated, the sum total of increase or decrease in carbon stock over the five pools is calculated. Any resulting decrease in carbon stock is converted into CO_2 emission equivalent. Any resulting increase is shown as CO_2 absorption equivalent in information tables. The carbon stock changes are converted into CO_2–emission and absorption by multiplying the resulting carbon stock changes by 44/12 (stoichiometric ratio between CO_2 and carbon) and sign conversion: carbon stock decrease (minus sign) results in atmospheric emission, carbon stock increase (plus sign) results in absorption. The carbon accumulated in harvested timber is not reported in the data as this is not considered to be a pool in terms of the Marrakesh Accords.

In the Russian Federation IIASA databank is used for forest carbon accounting (FCA) [9]. This databank comprises a complex GIS with characteristics of forests, lands and components of natural environment of the Russian Federation. Forest carbon accounting includes all carbon components connected with all terrestrial ecosystems. FCA development is based upon a hypothesis of global warming due to the enhanced greenhouse effect. This methodology represents global carbon balance as a sum total of the contributions of major carbon sources and absorbents over a certain period of time. FCA is mainly applied to terrestrial components. Main carbon reservoirs are soil, overground vegetation taken together, forests, wetlands, meadows, shrublands, large woody residues, dead vegetative residues covered by soil, agricultural and forest products. Data of state forest inventory summed up with growth models system and Russian forest productivity are used to assess carbon sequestration by this method. For lands covered with forest vegetation in Russia they calculate a parameter of net ecosystem carbon balance which is a full verified carbon budget of forests over a certain period [10].

The Centre for Environmental Problems and Forest Productivity under the Russian Academy of Sciences has developed a Method for Regional Forest Carbon Budget Assessment (RFCBA) [11]. This method uses data of State Forest Register (SFR) of the Russian Federation as a main data source to assess regional forest carbon budget. Due to the fact that the territory of Russia is split into different natural zones and carbon parameters of forests considerably vary across different zones and regions, the assessment method is based on the principle of zone-regional territorial division of Russia with allocation of macroregions [12].

Carbon of overground phytomass is calculated in terms of the wood stock volume cited by the SFR databank and conversion factors such as the ratio between carbon stock of overground phytomass and stem wood stock. The calculations are made using a system of conversion factors determined for prevailing tree species by age groups. The conversion factors are measured as physical density (tC/m^3) and make it possible to measure all overground phytomass (including stems, branches, needles and leaves) in terms of wood stock volume for economic purposes.

Calculation of the forest floor carbon is made by the area of any prevailing tree species and average unit-area value of carbon stock characteristic for zone-regional grounds. Calculation of soil carbon stock is similar to that of the forest floor, however it is made by reference average values of organic carbon in the 0–30 cm layer of soil.

Carbon stock is calculated for the following pools: overground and full phytomass of forest stands, dead wood (windblown and dead-standing), forest floor, upper 30-cm layer of soil. Then the carbon stock is summed up across the age groups to obtain total value for prevailing tree species and further for separate locations.

The calculations of the carbon pool values by age groups of forest stands serve as a basis to assess carbon flows (the methodology uses the term of “carbon absorption”). Equations are used to calculate average unit-area values of phytomass carbon stock in successive age groups. Then, average annual carbon absorption by a phytomass pool in a given age group is assessed by means of the time intervals a forest stand developed in the given age group. The sum total of carbon absorption by a phytomass pool in a given age group for prevailing species is considered to equal to the product of average annual value by the corresponding area. Carbon absorption by the phytomass pool in the oldest age group (overmature) is set to zero.

In Canada, in order to estimate carbon stock and balance for the forests throughout the country and in separate provinces they use the operational-scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS) which is a key constituent of the National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS) [13, 14]. Roughly this model can be called “one inventory + changes due to abiotic, biotic and anthropogenic factors” [2]. The calculations are based upon forest inventory data collected from experimental sites.

Nowadays CBM-CFS3 model is in use and it is built upon methodological level 3 of IPPC Guidelines for efficient land-use, land-use change and forestry [4]. The method at the heart of the model is focused on the simulation of carbon stock dynamics in overground and underground phytomass, dead organic substance including soils, and makes it possible to track carbon flows migration at landscape and regional levels. The CBM-CFS3 model simulates annual changes in carbon stock across a separate forest stand and carbon pool that are caused by the stand development, fall, mortality, organic substance transfer and forest floor decomposition. The model tracks 10 pools of biomass fractions and 11 pools of dead organic substance. In order to convert stem wood stock into overground phytomass fractions, the model uses equations established for all types of forest stands in Canada [15]. The rate of organic substance migration and carbon flow values due to fall, natural mortality, forest floor decomposition and organic substance transfer into one or several pools is assessed by a set of conversion factors that are determined by the analysis of percentage ratio between overground and underground phytomass fractions that annually replenish the dead organic substance pool.

The Institute of Physical-Chemical and Biological Problems of Soil Science (Russia) and European Forest Institute (Finland) have developed computer simulation model EFIMOD 2 [16] to describe the tree (stand) development and biological cycle of elements (carbon and nitrogen pools) in boreal and temperate forest ecosystems at local level. EFIMOD 2 enables short-term and long-term simulation of the dynamics of natural and managed forest ecosystems over a wide range of forest areas, climate conditions and silvicultural regimes. The model is effective for the assessment of stand productivity based on the location of trees, climate and soil impacts as well as forest management regimes in accordance to the criteria and characteristics of sustainable forest management.

EFIMOD 2 of "forest-soil" system comprises 4 components (models):

1) models of annual biomass increment of an individual tree (the model is based on the experimental findings of biological productivity of common pine (Pinus sylvestris L.), common spruce (Picea abies L. Karst) and drooping birch (Betula pendula L.) in Russian boreal forests);

2) individual spatial model of a stand composed of individual trees (the growth is simulated depending on the tree location within the stand and access of air, water and nutrients (tree competition for environmental factors));

3) dynamics models of soil organic substance ROMUL (used to assess organic substances dynamics and access to nitrogen for tree development depending on soil temperature and moisture, forest floor quality (structure)) [17];

4) special soil climate statistical simulator SCLISS (provides necessary monthly meteorological data for air and soil).

As input parameters (data) the system requires standard forest inventory data to include:

– tree species structure of the stand on a forest subcompartment;

– age;

– average stem length and diameter at 1.3 m height for each pure even-aged stand;

– the number of trees per 1 hectare;

– characteristics of pools of organic soil substance.

American computer budget model of local spatial level (U.S. FORest CARBon Budget Model (FORCARB2)) has been developed to assess the U.S. forests and is intended to estimate carbon stock and predict its fluctuations in the forest ecosystems and for forest products at 5 year intervals [18].

FORCARB2 Model estimates accumulated carbon stock by the following parameters (pools):

– Forest areas, i.e., areas of public forested lands, reserved forests and low-productive forested lands (the forest area being equal, the model accounts for the probability of carbon redistribution across the forest ecosystem components over the area, e.g., as a result of tree development, mortality or removal of trees (felling)). Main carbon sinks in the forest are trees (their overground and underground parts), dry-standing trees, dead wood (windblown trees), forest floor and soil. The model uses forest inventory data collected from experimental sites.

– Harvested wood products (HWP). Carbon distribution in the harvested wood products is estimated by four categories in the course of time:

1) useful products (including end products, i.e., timber used for house construction, wooden furniture, wooden containers and other items),

2) litter (it is assumed that carbon in landfills will be sequestered for the long run at a slow decomposition rate),

3) carbon contained in energy wood (mainly in disposed wood by-products processed by mills as well as wood burnt in public utility boilers to generate power or heat),

4) carbon emission without energy capture (including residues of mills or other wood products burnt or decomposed without capturing or using the heat released).

Russian mathematical simulation model FORRUS-S (FORest of RUSsia – Stand) is intended to predict the dynamics of taxation characteristics of uneven-aged multi-species stands over the areas of several dozens of thousands hectares (i.e., at local or regional spatial level) for a five-year period [19]. The model describes the dynamics of forest taxation characteristics (tree species structure and stand productivity over successive changes) in time and can be applied to estimate carbon balance dynamics rather than its calculation without soil carbon account. The model is of ecological-physiological class simulating processes of species birth, development and death.

FORRUS-S Model comprises four clusters:

– input data and parameters of the model (standard taxation description of subcompartments, forest stand plans, bioecological databanks, etc.);

– utility software;

– simulation (contains a "natural development" model (with 4 submodels: "light", "growth", "thinning", "recovery") and a "exogenous development" model);

– output data.

The research group of Ural State Forest Engineering University (Russia) has developed "Information System of Determination and Mapping of Carbon Sequestration in Forests" to assess the bioproductivity of forests. During field work model trees are selected on experimental sites and then split into fractions, i.e., stem wood, bark, leaves (needles), branch wood, branch bark, roots. The phytomass is weighed, the samples are then dried to remove moisture. This is a labour-consuming inventory method that enables calculation of all overground and underground fractions of phytomass from an experimental site as per a level of forest taxation subcompartment. The phytomass measurements make it possible to estimate net primary production of different fractions.

The research group of USFEU under the leadership of V.A. Usoltsev has compiled and published the most representative databank of production characteristics of forest stands in Northern Eurasia. The databank contains 8 thousand records of phytomass and 1.2 thousand records of primary net production (NPP) [20, 21]. This information has been complemented by State Forest Fund Inventory (SFFI) data and then used to create an assessment system for phytomass and NPP in forests. Primarily models have been identified that describe phytomass dependency of each fraction (stem bark, branches, needles, roots, lower storey) on the stand age and stock by tree species and age classes. A set of functions of phytomass fraction logarithm has been determined for net primary production (V.A. Usoltsev identifies it as carbon sequestration by forests). The resulting equations have been applied to calculate phytomass and net primary production in forestry establishments (forest district in the modern forest management structure) using the SFFI data.

Tables-matrixes have been created for the forestry establishments that show distribution of forest cover and stemwood stock by forest-forming species and age classes. The age groups have been converted into age classes with account of felling ages for wood harvest as prescribed by the forest inventory for each tree species. Models are tabulated by wood stock volume and stand age in each cell of table-matrixes for the forestry establishments. To calculate the phytomass stock over the total area, phytomass stock per a unit area is assessed and then multiplied by the forest cover of each cell. The sum total of the results for age classes shows total phytomass stock for each species separately. Further summing-up of phytomass stock by fractions and tree species results in total phytomass volume for the total area of each forestry establishment. The convergence algorithm of net primary production (NPP) model and data matrixes of the forestry establishments is similar to that of phytomass with the only difference that models are tabulated with inserting values of not only stemwood age and stock but also previously determined weight values of needles, root and lower storey. Determination and mapping of carbon sequestration by the forests can be done by ADABAS DBMS software and application editor Natural [2].

Estimation of the forest carbon budget is not envisaged by the Information System as it calculates only the budget input, i.e., net primary production.

The development of a methodology for determination of carbon weight and accumulation intensity in swamp forests and wetlands represent a particular important problem. It is obvious that slow mineralization of dead vegetation and its parts under excessive moisture will lead to long-term carbon storage. This process will be the most intensive in lowland bogs.

In the Republic of Belarus peat volumes in peatlands, water and carbon volumes in swamps are estimated by TCCP 17.12-08-2015 (33140) "Determination of uses of peatlands and swamps" [22]. According to the methodology, carbon stock in swamps is calculated by the formula (2.1):

$$W_C = P \times C_w \times C_A \times C_C, \tag{2.1}$$

where W_C – carbon weight, thousand t;

P – peat stock in swamps at reference peat humidity of 40% thousand t;

C_w – conversion factor of peat weight at reference humidity of 40% into absolutely dry substance, equal to 0.6;

C_A – ash coefficient averaging 0.963 for highland peat; 0.88 for lowland peat; 0.922 for mixed and transition peat;

C_C – coefficient of carbon content in absolutely dry peat substance averaging 0.556 for highland peat; 0.585 for lowland peat; 0,571 for mixed and transition peat.

When choosing optimal methods to determine the level of absorption of greenhouse gases for the conditions of the Republic of Belarus it is necessary to consider strengths and weaknesses of the currently existing methods as well as how the methods used in the conditions of the Republic of Belarus can assist in achieving objective information.

Basic forest inventory is carried out every 10 years in the Republic of Belarus. Annually current changes are added and subcompartment databank "Forest Fund of the Republic of Belarus" is updated. Every five years State Forest Fund Inventory is carried out, annually State Forest Cadastre of the Republic of Belarus is updated. Thus, the most unbiased and efficient forest carbon budget calculation occurs in forests with stand stock utilization (stemwood stock) determined by the forest fund inventory data.

Nowadays in the Republic of Belarus "Assessment methodology for annual flows of "carbon dioxide stock-emission and total carbon sequestration by the forests of the Republic of Belarus"" [23] has been developed and is being used to calculate total carbon sequestration and annual carbon dioxide "stock-emission" in forests when conducting national inventory of greenhouse gases. The methodology has been adapted to the guidelines for efficient land use, land use change and forestry of IPPC (2003). Therefore its application appears to be the most efficient.

To calculate carbon sequestration by phytomass an equation proposed by IPPC (2.2 and 2.3) is used. The equation is based upon "the calculation method by stock change":

$$C = V \cdot W \cdot BEF_2 \cdot (1+R) \cdot CF, \tag{2.2}$$

$$\Delta C_{FFLB} = (C_{t2} - C_{t1}) / (t2 - t1), \tag{2.3}$$

where C_{t2} and C_{t1} – total amount of carbon in phytomass of forest stands calculated at the time points t2 and t1 respectively, tC;

V – total volume of stands by state forest fund inventory (or Forest cadastre) data of the Republic of Belarus, m^3;

BEF_2 – phytomass factor to convert total stock volume (i.e. stemwood volume) into the value of phytomass of all components of overground stand, nondimensional value;

W – volume-weighted medium density of wood, tons of absolutely dry wood, t/m^3;

R – top-root (incl. stumps) ratio, nondimensional value;

CF – carbon share of dry substance;

ΔC_{FFLB} – annual change in carbon sinks over forested lands, tons of C per annum.

Data about wood density can be obtained from local sources. The share of carbon in dry phytomass can be derived by IPPC methods (2003) and can be set to 0.5 if local data are not available. BEF factors are "factors of biomass overgrowth (ratio between the volume of branches, offshoots, leaves, roots and stemwood volume)". The IPPC methods recommend to determine it by direct method on experimental areas or use available resources to derive local allometric equations.

To calculate carbon sequestration by forest stands, excluding wood weight, conversion factors (coefficients?) have been determined based on experimental sites data and relevant reference sources. The (coefficients?) are used to convert stemwood volume into the volume (weight) of young growth, understory, forest live cover in the stands of main forest-forming species, prevailing forest types and current age structure of the forests of Belarus.

Accumulation of soil carbon has been calculated by equation 4.3.3 proposed by the IPPC Program using national cadastres of greenhouse gases [24, p. 4, 123].

To measure the forest cover weight and its organic carbon content, data of the subcompartment databank "Forest Fund of the Republic of Belarus" and data of the analysis of forest cover samples carried out by RUE "Belgosles" on 410 constant inventory points when monitoring the forest health in 2001-2009 are used

Information about the volume of lying (windblown) and standing (dry) wood is contained in the subcompartment databank "Forest Fund of the Republic of Belarus". Values of carbon density and concentration for windblown and dry-standing wood have been proposed based on the review of findings by S.A. Zhdanovich and A.V. Pugachevskiy [25].

The review of total carbon sequestration by Belarusian forests is recommended to be carried out in the context of carbon pools. There are 19 pools in total (sequestered carbon groups).

Forest carbon pool 19 is total carbon content in a forest ecosystem (carbon in forest phytomass, organic carbon of 30-cm soil layer of forested lands, forest cover carbon and carbon in windblown wood) of the Republic of Belarus:

Pool 1 – carbon content in the phytomass of pine formation of the Republic of Belarus.

Pool 2 – carbon content in the phytomass of spruce formation of the Republic of Belarus.

Pool 3 – carbon content in the phytomass of oak formation of the Republic of Belarus.

Pool 4 – carbon content in the phytomass of birch formation of the Republic of Belarus.

Pool 5 – carbon content in the phytomass of black alder formation of the Republic of Belarus.

Pool 6 – carbon content in the phytomass of aspen formation of the Republic of Belarus.

Pool 7 – carbon content in the phytomass of other formations of the Republic of Belarus (larch, hornbeam, ash, maple, elm, grey alder, linden, poplar, woody willow, apple, etc.).

Pool 8 – carbon content in stemwood of the forests of the Republic of Belarus.

Pool 9 – carbon content in branches of the forests of the Republic of Belarus.

Pool 10 – carbon content in leaves and needles of the forests of the Republic of Belarus.

Pool 11 – carbon content in roots and stumps of the forests of the Republic of Belarus.

Pool 12 – carbon content in young growth and understory of the forests of the Republic of Belarus.

Pool 13 – carbon content in forest live cover of the forests of the Republic of Belarus.

Pool 14 – total carbon content in phytomass of the forests of the Republic of Belarus.

Pool 15 – carbon content in 30-cm soil upper layer of the forests of the Republic of Belarus.

Pool 16 – carbon content in forest cover of the forests of the Republic of Belarus.

Pool 17 – carbon content in windblown wood of the forests of the Republic of Belarus.

Pool 18 – carbon content in dry-standing wood of the forests of the Republic of Belarus.

To measure the carbon volume in swamps it is recommended to apply methods based on the calculations by TCCP ТКП 17.12-08-2015 (33140) [22].

2.2. Use of GIS "Forest Resources" for spatial reference of the calculation of absorption of greenhouse gases by forest fund areas

The data about forest stands volumes in Belarus used to calculate carbon budget have their own specific features and limitations [6].

Basic forest inventory is carried out in Belarusian forests by category I of forest inventory every 10 years. Annually current changes are added and the subcompartment databank "Forest Fund of the Republic of Belarus" is updated. Every five years State Recording of Forest Fund is done. State Forest Cadastre is created every year. These facts provide for unbiased substantiation of carbon budget calculation in forests with the use of stand volume data (i.e., stemwood volume) as defined by forest fund recording and (or) Forest Cadastre of the Republic of Belarus.

State Forest Cadastre (SFC) is based on forest inventory projects. The SFC contains data about all tree species, their age structure, wood volumes for every government body in charge of forests.

The accuracy of taxation is integral to the quality of forest inventory operations. Accuracy requirements are set by the Forest Code and depend on the tasks that are solved by the forest management bodies. They are as well regulated by the norms of maximum allowable errors when determining the taxation parameters and the prescribed confidence level [39, 40].

Depending on the stand category, the accuracy standards for taxation parameters are determined [40].

Due to the fact that the core carbon volume is sequestered in the phytomass of forest stands, better accuracy of determination of greenhouse gases absorption is primarily ensured by the accuracy of determination of stemwood volume.

Allowable accidental error in determining average volume per 1 ha is set to ±15–20%. Since calculation of the carbon budget in Belarusian forests is made in terms of stand volumes (i.e., stemwood volume) with the use of forest record and forest cadastre data, the value of allowable accidental error is applied to carbon budget as well, i.e., allowable accidental error in the determination of greenhouse gases absorption can be set to ±15–20%.

Better accuracy of carbon budget calculation is directly linked to the taxation accuracy. Development of new improved methods and tools of terrestrial taxation driven by the latest achievements of technical progress is indispensable for collecting reliable data about forest resources.

More accurate carbon measurement in stand components can be achieved through better accuracy of determining weight ratio factors in dry-weight fractions of a stand (stemwood, branches, needles and leaves, roots and stumps) as well as forest stand components (young growth and understory, forest live cover) per 1 m^3 of stemwood. To improve this parameter, field studies must be carried out on experimental sites in terms of forest-forming tree species under various forest growth conditions. It is recommended to do a more detailed study of forested lands across different forest type series with detailed soil mapping showing the most relevant soil characteristics. Data about forest floor dry weight per 1 m^3 of stemwood also need to be defined when doing field studies across forest formations. To clarify the volume of windblown and dry-standing wood in Belarusian forests it is required to allocate experimental sites under various forest growth conditions.

Single multilevel forestry GIS developed in Belarus can be used for spatial reference of the calculation of absorption of greenhouse gases by forest fund areas based on the methodology [6].

The first GIS "Forest Resources" was developed in Belarus in 1992–1995. Since 1995 GIS "Forest Resources" has been gradually applied for forestry purposes. In 2000–2002 a technology for automated creation of accurate plan-cartographic forest inventory materials was developed by the experts of RUE "Belgosles". In 2013 digital maps for all forestry enterprises of the Republic of Belarus was finalized. Digital spatial models consolidate digital cartographic and taxation information for a site.

The technology has the following advantages:

– accurate reference of forest sites to geodesic data;

– absolute accuracy of adjustment of forestry enterprise boundaries to adjacent land users and to each other;

– consistency of forest digital maps and digital maps of other agencies and land users;

– possibility to generate thematic maps of any scale and content.

Accurate reference of forest sites to geodesic data makes it possible to generate thematic maps of any site of the republican forest fund (subcompartment, forest quarter, forestry section, forestry enterprise, administrative-territorial unit, republic-wide).

Integrity of cartographic and taxation databanks enable generation of required thematic maps or obtaining basic data for further calculations.

Spatial reference of the calculation of absorption of greenhouse gases by forest fund areas can be exemplified by the calculation of carbon accumulation by a forest fund area, ***e.g. Glussk district of Mogilev region***.

To estimate biomass and carbon stock we apply methodology developed by Intergovernmental Panel on Climate Change. The methodology is used for the estimation of forest resources at a global level.

According to the methodology total carbon stock in forest ecosystems includes:

– accumulation of carbon in live biomass (overground and below surface);

– accumulation of carbon in dry-standing and windblown wood;

– accumulation of carbon in forest litter;

– accumulation of carbon in soil.

The integral cartographic and taxation databank “Forest Resources” provides us with basic data for further calculation of the required parameters (Table 1). In the example given national complex parameter of basic density of each forest-forming tree species is applied to calculate the biomass volume for each tree species. If it is necessary to obtain more accurate results, GIS “Forest Resources” as well as national basic density factors for all age groups enable calculations for each tree species by age groups.

Biomass growth factor (BGF) proposed by Intergovernmental Panel on Climate Change (IPCC) for coniferous and deciduous species is applied to calculate living overground biomass, including stemwood, stump, bark, seeds and leaves (Table 1).

Ratio factor for underground (all living roots) and overground biomass is applied to calculate the volume of living biomass below surface (Table 1).

Integral cartographic and taxation databanks enable us to calculate total volume of dead wood, i.e., dry-standing and windblown wood (Table 1). Factor 0.5 is applied to convert total dead wood volume into biomass volume without using biomass growth factor.

Standard global value of carbon share equaling 0.47 is applied to convert biomass volumes of dry-standing and windblown wood into carbon content in biomass.

Table 1

Calculation of biomass volume of growing trees, dry-standing and windblown wood

Tree species	Stand volume (thousand m^3)	Basic density (t/m^3)	Stemwood biomass (thousand t)	Biomass growth factor (BGF)	Overground biomass (thousand t)	Root-shoot ratio	Biomass below surface (thousand t)
Biomass of growing trees							
Pine	11379	0.42	4779	1.35	6452	0.32	2065
Spruce	753	0.40	301	1.35	406	0.32	130
Oak	415	0.58	241	1.30	313	0.35	110
Ash	36	0.57	21	1.30	27	0.35	9
Hornbeam	24	0.63	15	1.30	19	0.35	7
Maple	30	0.52	16	1.30	21	0.35	7
Birch	1663	0.51	848	1.30	1102	0.26	286
Aspen	143	0.35	50	1.30	65	0.24	16
Black alder	1168	0.45	526	1.30	684	0.26	178
Other species	1	0.49	1	1.325	1	0.30	–
Total	**15612**	–	**6798**	–	**9090**	–	**2808**
Non-living biomass (dry-standing and windblown wood)							
Dead wood, total	172	–	86	–	86	x	x
including: dry-standing	97	0.50	48	1.00	48	x	x
debris	75	0.50	38	1.00	38	x	x

The calculation of organic carbon content in forest floor (Table 2) and soil (Table 3) has been made by the methodology developed in Belarus [41].

Table 2

Organic carbon accumulation by forest soils

Forest type series	Area, ha	Organic carbon concentration in soil, gC/kg	Volume density of soil, g/cm^3	Coarse soils fractions (fractions > 1 mm), %	Carbon accumulation, t
Heather	3081	6.0	0.95	1.05	17377
Vaccinium	115	6.2	1.0	1.05	705
Mossy	20218	9.5	1.10	1.10	208954
Bracken	7762	11.4	1.20	1.20	104060
Wood-sorrel	7263	16.0	1.30	1.30	146538
Myrtillus	14136	23.6	1.25	1.20	408672
Long-mossy	4338	293.5	0.30	1.00	381961
Ledum	1422	365.8	0.25	–	130042
Sedge	2091	313.4	0.25	–	163830
Sedge-sphagnum	1793	338.9	0.25	–	151912
Aegopodium	691	36.3	1.35	1.50	32169
Urticaceous	1685	203.9	0.80	–	274857
Ferny	3072	305.0	0.25	–	234240
Riverine-grassy	2237	349.8	0.25	–	195626
Grass-floodplain	53	17.1	1.30	–	1178
Total	**69957**				**2450943**

Table 3

Calculation of organic carbon in forest floor

Prevailing tree species (forest formation)	Stem wood volume, thousand m^3	Weight of dry-weight forest floor per 1 m^3 of stemwood, t/m^3	Carbon share in dry-weight forest floor	Organic carbon accumulation in forest floor, thousand t
Pine	11379	0.100	0.460	523
Spruce	753	0.095	0.432	31
Oak, ash, hornbeam, maple	505	0.030	0.433	7
Birch	1663	0.010	0.400	7
Black alder	1168	0.010	0.400	5
Aspen	143	0.006	0.500	1
Other	1	0.037	0.486	–
Total	**15612**			**574**

Carbon content, volume density of soil and share of coarse fractions have been determined based on the analysis of soil samples taken from the forest fund of the Republic of Belarus.

Weight of forest floor has been measured by stemwood volume. Conversion factors of carbon content in forest floor and weight of forest floor per 1 m^3 of stemwood have been taken from reference sources and materials of experimental sites established in the national forest fund.

Total carbon content on one forest fund area taken as an example equals 8657 thousand t, including:

in biomass of overground part of a stand – $9090 \times 0.47 = 4272$ thousand t.

in biomass of underground part of a stand – $2808 \times 0.47 = 1320$ thousand t.

in biomass of dry-standing and windblown wood – $86 \times 0.47 = 40$ thousand t.

in forest floor – 574 thousand t.

in forest soil – 2451 thousand t.

Carbon content in 1 ha of forested lands (70920 ha) equals 123,2 t, which is below average European parameter (161 t/ha by FRA data, 2010). The divergence results mainly from carbon content in forest soils, i.e., 35 t/ha as compared to 96 t/ha. This can be explained by forest soils structure in the taken example of forest fund area (upland forest with low carbon accumulation in soil and forest floor occupy over 75% of the total territory).

To calculate the total volume of carbon sequestration by forest fund areas, additional calculation of carbon sequestration by non-forested lands, open forest plantations and certain types of non-forest lands (swamps, agricultural lands, etc.)

The given example of calculation of carbon sequestration does not pretend to be absolutely accurate. The main goal of the calculation is to illustrate the uses of cartographic and taxation databank of GIS "Forest Resources" to provide spatial reference to carbon dioxide adsorption by the forest fund areas.

Integrated of cartographic and taxation databank of GIS "Forest Resources" has a substantial drawback of data inconsistency. Both databanks are mutually consistent only when they updated by the results of basic forest inventory every 10 years.

Thereafter the taxation databank is updated annually by entering current changes resulting from economic activity of forestry enterprises. When annual current changes are entered, the aftereffects of forestry catastrophic events are fully considered. Every five years the forest fund is updated.

Cartographic databank is not updated in a similar way. During previous years all current changes of the reporting year were entered into the cartographic databank and forest inventory map-boards based on the results of ongoing forest inventory. This work has been ceased since the ongoing forest inventory was discontinued.

Electronic cartographic databanks of the whole forest fund have been created and handed over to the legal entities of the forest sector, so it is required to develop a software package for continuous entry of the current changes into both taxation and cartographic databanks by the legal entities with subsequent data transfer to the central server.

Cartographic and subcompartment databanks of GIS "Forest Resources" make it possible to apply any of the available GIS-data-based methods for the calculation of greenhouse gases absorption by the forest fund areas as well as to estimate their carbon sequestration capacity.

At the same time, information about carbon flows and its annual sequestration by the forest fund areas is of greater importance for practical application. The carbon sequestration capacity is directly dependent on annual current increment of carbon. So, data from permanent forest monitoring stations can be widely used for these purposes.

Experts of RUE "Belgosles" established 410 permanent monitoring stations (PMS) located on the transnational network (16×16 km) covering the total forest fund area of the country. At the stations (PMS) measurements of the circumference, height and other prescribed parameters of the trees under monitoring were done at regular intervals in order to register current changes in the forest fund. Samples of forest soils and forest floor were taken at all PMS. The soil samples were taken by soil layers and at fixed depths. The analysis of the samples was carried out in the analytical laboratory of RUE "Belgosles" with the use of appropriate methods. The samples were analyzed for carbon and other chemical elements. Electronic databank was created.

The instrumental measurements of the circumference and height of the trees under monitoring ensure high accuracy of determination of the current increment over a five-year period (measurement interval – 5 years) across principal forest-forming species on a nationwide scale and individual forest fund areas. These data combined with the amount of dead wood estimated at PMS make it possible to calculate annual carbon sequestration by forest vegetation.

Average annual carbon sequestration by forest soils and forest floor can also be estimated by the data obtained from the soil analysis at PMS of forest monitoring. However, in order to determine average annual changes in carbon content the soil samples must be taken for a second time with subsequent laboratory analysis. After that the required values can be obtained by simple calculations.

3

DETERMINATION OF CARBON RESERVES AND FLOWS (POOLS) IN THE FOREST FUND OF BELARUS

Calculation of the total carbon amount in the phytomass of Belarusian forests is made in terms of forest-forming tree species (prevailing species) and can be summarized in the table below (Table 4).

Total stand volume (V) is established for the target year by the data of state forest fund inventory or Forest Cadastre of the Republic of Belarus.

The phytomass of stand components per one unit of volume in terms of prevailing species is determined based on the available relations between different fractions of wood phytomass (stem, branches, needles, leaves, stump, roots). The density of dry phytomass, the carbon share in stemwood and fractions of prevailing species is identified based on the analysis of data from experimental sites and renowned reference sources (IPPC materials [24], ECE UN FAO [26], S.V. Belov) [27], V.V. Smirnov [28], A.A. Molchanov [29], L.P. Smolyak, A.I. Rusalenko and E.G. Petrov [30], I.D. Yurkevich and E.P. Yaroshevich [31], N.A. Vnuzdaev, O.V. Shakhova and V.I. Stukalova [32], V.A. Usoltsev and S.V. Zalesov [33], N.I. Bazilevich [34], D.G. Zamolodchikov and A.I. Utkin [35], A.I. Utkin, D.G. Zamolodchikov and A.A. Pryazhnikov [36].

Basic data for the calculation of conversion factors CV cited in Table 4 are listed in Appendixes A and B [23].

In particular, dry weight of individual stand fractions (stemwood, branches, needles or leaves, roots and stump) as well as individual stand components (young growth and understory, forest live cover) per 1 m^3 of stemwood is given in Appendix A. Carbon share of dry phytomass of different stand fractions and components is given in Appendix B [23].

Table 4

Algorithm calculation of the carbon sequestration by the phytomass of Belarusian forests

Indicators	Forest-forming tree species							Total carbon amount (pools) in stand components
	Pine	Spruce	Oak	Birch	Black alder	Aspen	Other	
Total stand volume V, thousand m^3	V_1	V_2	V_3	V_4	V_5	V_6	V_7	
Carbon share C in stand components per one unit of **volume** V, **CV**, tC/m^3								
Stemwood "1"	C_1V_1	C_1V_2	C_1V_3	C_1V_4	C_1V_5	C_1V_6	C_1V_7	
Branches "2"	C_2V_1	C_2V_2	C_2V_3	C_2V_4	C_2V_5	C_2V_6	C_2V_7	
needles (leaves) "3"	C_3V_1	C_3V_2	C_3V_3	C_3V_4	C_3V_5	C_3V_6	C_3V_7	
roots and stumps "4"	C_4V_1	C_4V_2	C_4V_3	C_4V_4	C_4V_5	C_4V_6	C_4V_7	
young growth and understory "5"	C_5V_1	C_5V_2	C_5V_3	C_5V_4	C_5V_5	C_5V_6	C_5V_7	
forest live cover "6"	C_6V_1	C_6V_2	C_6V_3	C_6V_4	C_6V_5	C_6V_6	C_6V_7	
Total carbon amount in stand components C, thousand tC								
stemwood	$V_1 \cdot C_1V$	$V_2 \cdot C_1V$	$V_3 \cdot C_1V$	$V_4 \cdot C_1V$	$V_5 \cdot C_1V$	$V_6 \cdot C_1V$	$V_7 \cdot C_1V$	$\sum V_n \cdot C_1V$ Pool 8
Branches	$V_1 \cdot C_2V$	$V_2 \cdot C_2V$	$V_3 \cdot C_2V$	$V_4 \cdot C_2V$	$V_5 \cdot C_2V$	$V_6 \cdot C_2V$	$V_7 \cdot C_2V$	$\sum V_n \cdot C_2V$ Pool 9
needles (leaves)	$V_1 \cdot C_3V$	$V_2 \cdot C_3V$	$V_3 \cdot C_3V$	$V_4 \cdot C_3V$	$V_5 \cdot C_3V$	$V_6 \cdot C_3V$	$V_7 \cdot C_3V$	$\sum V_n \cdot C_3V$ Pool 10
roots and stumps	$V_1 \cdot C_4V$	$V_2 \cdot C_4V$	$V_3 \cdot C_4V$	$V_4 \cdot C_4V$	$V_5 \cdot C_4V$	$V_6 \cdot C_4V$	$V_7 \cdot C_4V$	$\sum V_n \cdot C_4V$ Pool 11
young growth and understory	$V_1 \cdot C_5V$	$V_2 \cdot C_5V$	$V_3 \cdot C_5V$	$V_4 \cdot C_5V$	$V_5 \cdot C_5V$	$V_6 \cdot C_5V$	$V_7 \cdot C_5V$	$\sum V_n \cdot C_5V$ Pool 12
forest live cover	$V_1 \cdot C_6V$	$V_2 \cdot C_6V$	$V_3 \cdot C_6V$	$V_4 \cdot C_6V$	$V_5 \cdot C_6V$	$V_6 \cdot C_6V$	$V_7 \cdot C_6V$	$\sum V_n \cdot C_6V$ Pool 13
Total carbon amount (pools) in prevailing species stands, thousand tC	$\sum CV_1$ Pool 1	$\sum CV_2$ Pool 2	$\sum CV_3$ Pool 3	$\sum CV_4$ Pool 4	$\sum CV_5$ Pool 5	$\sum CV_6$ Pool 6	$\sum CV_7$ Pool 7	$\sum CV$ Pool 14

The conversion factors CV derived from these data (Appendixes A and B) are shown in Table 5.

Table 5

Carbon share in stand components per one unit of volume in terms of prevailing tree species CV [tC/m^3]

Prevailing tree species	Conversion factors CV, tC/m^3 of stand					
	Stemwood	Branches	Needles or leaves	Roots and stump	Young growth and understory	Forest live cover
Pine – 1	0.268	0.050	0.012	0.046	0.0005	0.004
Spruce – 2	0.235	0.034	0.038	0.044	0.0005	0.001
Oak – 3	0.343	0.142	0.027	0.072	0.0005	0.006
Birch – 4	0.300	0.047	0.024	0.050	0.0005	0.005
Alder (black) – 5	0.275	0.060	0.025	0.047	0.0005	0.001
Aspen – 6	0.224	0.027	0.018	0.045	0.0005	0.0005
Other – 7	0.138	0.037	0.016	0.020	0.0005	0.008

The values of the above indicators are determined from the data of soil-forest-typological study of the forested lands in Belarus updated by the analysis results (every 10 years) of soil samples taken in the course of forest monitoring in Belarus.

The soil carbon stock per a unit area expressed in volume is calculated by the equation (3.1) recommended by the IPCC program using national greenhouse gases cadastres [24, p. 4, 123] in the following way:

$$SOC = [SOC] \times \text{Volume density} \times \text{Depth} \times \times \text{Coarse fractions} \times 10 \quad (3.1)$$

where SOC – organic carbon stock in soil, MgC/ha;

[SOC] – concentration of soil organic carbon in a given soil, gC/kg soil (based on laboratory analysis);

Volume density – soil weight per sample volume, mg/m^3;

Depth – depth of sample taking, thickness or soil layer, m;

Coarse fractions – 1 – (% of coarse fractions volume/100);

10 – finite factor for converting the measurement units into MgC/ha.

The values of the above indicators are based on the materials of soil-forest-typological study of the Belarusian forest lands. They are adjusted by the analysis data of soil samples (every 10 years) taken during monitoring of the Belarusian forests.

Carbon content, volume density of soil, share of coarse fractions (fraction > 1 mm) are measured by the analytical results from 367 specific and mixed soil samples taken from the forest fund of the Republic of Belarus by the experts of RUE "Belgosles" in 2001–2009. The laboratory analyses were carried out for soil horizon covering 30-cm soil layer in the central laboratory of the Ministry of Forestry (RUE "Belgosles") certified by the National Accreditation Body (Gosstandart of the Republic of Belarus). The concentration of soil organic carbon was determined by Tyurin Method. The values obtained were grouped by forest type series and shown as average values.

The established average parameters for soil organic carbon calculation in the forested lands of Belarus as of 01.10.2010 are given in Table 6.

Table 6

Basic data for soil organic carbon calculation in the upper 30-cm soils layer of Belarusian forested lands

Forest type series	CC_{soil} – concentration of soil organic carbon, gC/kg	P_{soil} – volume density of soil, g/cm^3	S_{soil} – coarse fractions in soil (fractions > 1 mm), %
Heather	6.0	0.95	1.05
Vaccinium	6.2	1.0	1.05
Mossy	9.5	1.10	1.10
Bracken	11.4	1.20	1.20
Wood-sorrel	16.0	1.30	1.30
Myrtillus	23.6	1.25	1.20
Long-mossy	293.5	0.30	1.00
Ledum	365.8	0.25	–
Sedge	313.4	0.25	–
Sedge-sphagnum	338.9	0.25	–
Aegopodium	36.3	1.35	1.50
Urticaceous	203.9	0.80	–
Ferny	305.0	0.25	–
Riverine-grassy	349.8	0.25	–
Grass-floodplain	17.1	1.30	–

General form of equation (3.2) to calculate organic carbon amount in the upper 30-cm soil layer of Belarusian forested lands looks as follows:

$$C_{soil} = KC_{soil} \cdot P_{soil} \cdot (1 - S_{soil}/100) \cdot 3, \qquad (3.2)$$

where C_{soil} (Pool 15) – organic carbon accumulation in the upper 30-cm soil layer of Belarusian forested lands, [tC];

KC_{soil} concentration of organic carbon in the upper 30-cm soil layer of Belarusian forested lands, [gC/kg];

P_{soil} – volume density of the upper 30-cm soil layer of Belarusian forested lands, [g/cm^3];

S_{soil} – share of coarse fractions (fractions > 1 mm) in the upper 30-cm soil layer of Belarusian forested lands, [%];

3 – finite factor to convert carbon weight into t/ha, [10 t·cm^3].

General form of equation (3.3) to calculate the carbon amount in the forest cover looks as follows:

$$C_{fc} = W_{fc} \cdot KC_{fc}, \quad (3.3)$$

where C_{fc} – accumulation of organic carbon by forest cover, [tC];

W_{fc} – absolutely dry weight of forest cover, [t];

KC_{fc} – carbon share in the dry weight of forest cover, nondimensional value.

The weight of forest cover depends on the tree species structure of forest stand, its component structure (standing trees, young growth, understory, forest live cover), stand age and normality, soil-forest-type conditions affecting the decomposition intensity of the forest floor. The weight of forest cover is calculated by the formula (3.4):

$$M_{ff} = V_{sw} \cdot KM_{ff}, \quad (3.4)$$

where V_{sw} – stemwood volume [m^3/ha];

KM_{ff} – absolutely dry weight of forest floor in a stand per 1 m^3 of stemwood, [t/m^3].

Stemwood volume can be obtained from the subcompartment databank "Forest Fund of the Republic of Belarus" or other forest inventory data.

To determine the conversion factors KM_{ff} we used data from a wide collection of reference sources [26–36], findings obtained from own experimental sites established by the staff and pre-graduation students of the Silviculture Department of Belarusian State Technological University. The carbon share in forest floor was measured in similar way. These values are given in terms of forest formations (prevailing tree species) for average silviculture-taxation characteristics of forest formations as of 01.01.2010 (Table 7).

General form of equation (3.5) to calculate accumulation of organic carbon by forest floor in the forest stands of Belarus is as follows:

$$C_{ff} \text{ (Pool 16)} = V_{sw} \cdot KM_{ff} \cdot KC_{ff}, \text{ [tC/ha]}. \quad (3.5)$$

Table 7

Basic data to calculate organic carbon amount in forest floor of Belarusian forests

Prevailing tree species (forest formation)	V_{sw} – stemwood volume, m^3	KM_{ff} – absolutely dry weight of forest floor per 1 m^3 of stemwood, t/m^3	KC_{ff} – carbon share in the dry weight of forest floor	C_{ff} – organic carbon accumulation in forest floor, [tC]
Pine	From subcompartment databank “Forest Fund of the Republic of Belarus”	0.100	0.460	Measured by the relevant equation
Spruce		0.095	0.432	
Oak		0.030	0.433	
Birch		0.010	0.400	
Alder (black)		0.010	0.400	
Aspen		0.006	0.500	
Other		0.037	0.486	

Dead wood can be divided into fallen (windblown) and standing (dry-standing). The data about dead wood volume are collected during forest inventory and are entered into the subcompartment databank “Forest Fund of the Republic of Belarus”.

To calculate organic carbon content in dead wood, the following equations (3.6 and 3.7) are used:

$$C_{wbw}(\text{Pool } 17) = V_{wbw} \cdot KM_{WBW} \cdot KC_{WBW}, \quad (3.6)$$

$$C_{dsw}(\text{Pool } 18) = V_{dsw} \cdot KM_{DSW} \cdot KC_{DSW}, \quad (3.7)$$

where C_{wbw} – accumulation of organic carbon by windblown wood, [tC];

V_{WBW} – volume of windblown wood, [m^3], as in the subcompartment databank;

KM_{WBW} – volume density of dry windblown wood, [t/m^3];

KC_{WBW} – carbon share of dry windblown wood;

C_{dsw} – accumulation of organic carbon by dry-standing wood, [tC];

V_{DSW} – volume of dry-standing wood, [m^3], as in the subcompartment databank;

KM_{DSW} – volume of dry-standing wood when dry, [t/m^3];

KC_{DSW} – carbon share of dry-standing wood.

Values of carbon density and concentration for dead wood are established as follows [37]:

$$KM_{WBW} = 0.3 \text{ t/m}^3, \qquad KM_{DSW} = 0.5,$$

$$KC_{WBW} = 0.5 \text{ t/м}^3, \qquad KC_{DSW} = 0.5.$$

Annual or average-periodic carbon sequestration by forests is generally determined by the equation:

$$\pm\Delta C_t = (C_{t2} - C_{tl}) / (t_2 - t_1),$$

where $\pm\Delta C_t$ – annual or average-periodic annual carbon flow, thousand t/year;

C_{t2} – total carbon sequestration by forest at time point t_2, thousand tC;

C_{tl} – total carbon sequestration by forest at time point t_1 thousand tC;

t_2 – calendar year of measurements (e.g., 2010);

t_1 – calendar year of the previous measurements (e.g., 2005).

Under the value $+\Delta C_t$ there is "sink" (absorption) of atmospheric carbon in place. Under the value $-\Delta C_t$ there is carbon "emission" into the atmosphere.

In information tables annual values of carbon flow (increase or decrease in carbon accumulation by pools) are converted into CO_2 equivalent. Stoichiometric ratio between CO_2 and carbon (C) is equal to 44/12.

Calculation example: 150tC equals 550 t CO_2 ($150 \cdot 44/12$).

Calculations of annual (or average-periodic annual) carbon flow can be summarized in Tables 8 and 9.

As has been noted before, when estimating the carbon volumes sequestered by swamps it is recommended to use calculation-based methods in accordance with TCCP 17.12-08-2015 (33140) [22].

Decrease in peat volumes as compared to the original stock can be attributed to the following factors:

– industrial peat digging;

– losses in organic substance as a result of peat mineralization when draining and agricultural exploitation of peat lands.

Table 8

Calculation of annual carbon flows in terms of prevailing tree species

Indicators	Carbon pools (CV from Table 1) in terms of prevailing species, thousand tC							Total carbon pool in forests, thousand tC
	Pool 1	Pool 2	Pool 3	Pool 4	Pool 5	Pool 6	Pool 7	
	Pine	Spruce	Oak	Birch	Black alder	Aspen	Other	
C_{t2}	CV_{1t2}	CV_{2t2}	CV_{3t2}	CV_{4t2}	CV_{5t2}	CV_{6t2}	CV_{7t2}	CV_{t2}
C_{t1}	CV_{1t1}	CV_{2t1}	CV_{3t1}	CV_{4t1}	CV_{5t1}	CV_{6t1}	CV_{7t1}	CV_{t1}
ΔC_t	ΔC_{1t}	ΔC_{2t}	ΔC_{3t}	ΔC_{4t}	ΔC_{5t}	ΔC_{6t}	ΔC_{7t}	ΔC_t

Table 9

Calculation of annual carbon flows in terms of forest stand components

Indicators	Carbon pools ($V_n \cdot C_nV$ from Table 1) in terms of forest stand components, thousand tC						Total carbon pool in forests, thousand tC
	Pool 8	Pool 9	Pool 10	Pool 11	Pool 12	Pool 13	
	stemwood	branches	needles or leaves	roots and stump	young growth and understory	forest live cover	
C_{t2}	$V_n \cdot C_1V_{t2}$	$V_n \cdot C_2V_{t2}$	$V_n \cdot C_3V_{t2}$	$V_n \cdot C_4V_{t2}$	$V_n \cdot C_5V_{t2}$	$V_n \cdot C_6V_{t2}$	CV_{t2}
C_{t1}	$V_n \cdot C_1V_{t1}$	$V_n \cdot C_2V_{t1}$	$V_n \cdot C_3V_{t1}$	$V_n \cdot C_4V_{t1}$	$V_n \cdot C_5V_{t1}$	$V_n \cdot C_6V_{t1}$	CV_{t1}
ΔC_t	ΔC_{8t}	ΔC_{9t}	ΔC_{10t}	ΔC_{11t}	ΔC_{12t}	ΔC_{13t}	ΔC_{Vt}

To determine the remaining peat reserves data defined in [38] as of 01.01.1978 are taken as a point of reference.

The remaining peat reserves are calculated by the formula (3.8):

$$P_{rmn} = P_{rmn1978} - P_{dug} - P_{min}, \quad (3.8)$$

where P_{rmn} – remaining geological peat reserves as of the calculation period, thousand t;

$P_{rmn1978}$ – remaining geological peat reserves with reference to [23] as of 01.01.1978,thousand t;

P_{dug} – peat reserves dug, thousand t; the value is calculated by reporting data of the peat-digging enterprises, including reporting data of the enterprises involved in peat digging in 1970s–1990s (enterprises under the Ministry of Regional Industry, Belselkhozkhimiya, Ministry of Fuel Industry);

P_{min} – peat losses due to mineralization of the peat organic substance when draining and agricultural exploitation of peat lands, thousand t;

If the reporting data are not available, the peat reserves dug from a specified peatland are calculated by the formula (3.9):

$$P_{dug} = P_{rmn1978} \times S_{dug} / S_{inds}, \quad (3.9)$$

where S_{dug} – area of the worked-out peatland (defined by the data of state production association “Beltopgas” and state research institute “Institute for Nature Management” of Belarus NAS), ha;

S_{inds} – peatland area within the boundaries of peat formation depth with reference to [38] as of 01.01.1978, ha.

Peat losses due to mineralization of peat organic substance when draining and agricultural exploitation of peatlands are calculated by the formula (3.10):

$$P_{min} = K \times S_{agr} \times p \times n, \qquad (3.10)$$

where K – accounting factor of the area within the boundaries of peat formation depth that is used for agricultural purposes in relation to the area within zero boundaries;

S_{agr} – area (by the data of regional land use), ha;

p – average value of peat losses due to its mineralization per 1 ha at reference moisture content of 40%, equals 9.6 t/year;

n – number of years in the calculation period.

$$K = S_{inds} / S_0, \qquad (3.11)$$

where S_0 – peatland area within zero boundaries, ha.

Peat reserves within swamp boundaries are calculated by the formula (3.12):

$$P = S / S_0 \times P_{rmn}, \qquad (3.12)$$

where P – peat reserves in swamps (their area) under special protection, at reference peat moisture content of 40%, thousand t;

S – area of swamps, ha.

Carbon volume in swamps (their areas) are calculated by the formula (3.13):

$$W_C = P \times F_w \times F_A \times F_C, \qquad (3.13)$$

where W_C – carbon weight, thousand t;

P – peat reserves in swamps at reference peat moisture content of 40%, thousand t.

F_w – conversion factor of peat weight under 40% moisture content into absolutely dry substance, equals 0.6;

F_A – ash content factor averaging; 0.963 for highland peat; 088 for lowland peat; 0.922 for mixed and transition peat;

F_C – accounting factor of carbon content in absolutely dry peat substance averaging: 0.556 for highland peat; 0.585 for lowland peat; 0.571 for mixed and transition peat.

The above listed key indicators (Tables 5–9) are applied to calculate carbon flows in the forest fund of the Republic of Belarus based on the approved methodology [6]. Application of the methodology [6] provides rather high accuracy of calculation of carbon sequestration by Belarusian forests which is ensured by regularly updated subcompartment and cartographic databank “Forest Resources” GIS. Therefore the methodology [6] can be updated to a higher-status regulation, i.e., TCCP “Calculation rules for absorption and emission of greenhouse gases by the forest fund components.”. This measure is contained in the National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030 (Table 45). Calculations of greenhouse gases in the forest fund [6] are made only for carbon dioxide due to the fact that absorption/emission of other greenhouse gases such as nitrogen oxide, methane, fluorophtorocarbons are very insignificant.

4

CARBON BUDGET OF THE FOREST FUND OF BELARUS

4.1. Forests of Belarus as a source of absorption of greenhouse gases

Dynamic development of the forest ecosystem in Belarus has a sustained tendency for increasing forest productivity and wood stock (Table 10).

Table 10

Forest fund dynamics in the Republic of Belarus

Inventory years	Total forest fund area, thousand ha	Total wood stock, million cubic metres	Average wood stock per 1 ha, cubic metres	Total wood stock dynamics, million cubic metres
1945	6159.0	321.20	70	12.4
1956	7345.3	490.20	77	17.3
1961	8014.0	470.17	70	18.3
1973	8205.1	697.60	99	19.4
1983	8264.9	732.89	102	20.0
1994	8676.1	1093.23	148	20.7
2004	9341.0	1382.40	178	26.8
2014	9477.2	1692.70	207	31.9
2017	9565.8	1772.50	215	37.6

Over the period from 1945 to 2017 the total forest fund area has increased in 1.55 times (+3406.8 thousand ha), productivity (average wood stock) in 3.1 times (+125 cubic metres per 1 ha), total wood stock in 5.5 times (+1451.3 million cubic metres). This was made possible through effective forestry operations of forest regeneration and forest growing, measures on increasing productivity and improving forest care, rational forest utilization, etc.

Increase of wood stock and phytomass of the forest ecosystem respectively leads to enhanced carbon net flow from the atmosphere to forest with its subsequent absorption. Since 1956 (first post-war forest inventory) the carbon content has increased in the forest fund. As of 01.01.2017 the carbon pool of the forest fund of the Republic of Belarus comprised 3492.7 million ton (Figure 1). The increase of the forest fund area in 1.3 times resulted in the subsequent increase of carbon pool in 2.52 times. The carbon increment is almost twice as much as the forest fund increment. This resulted from a number of factors.

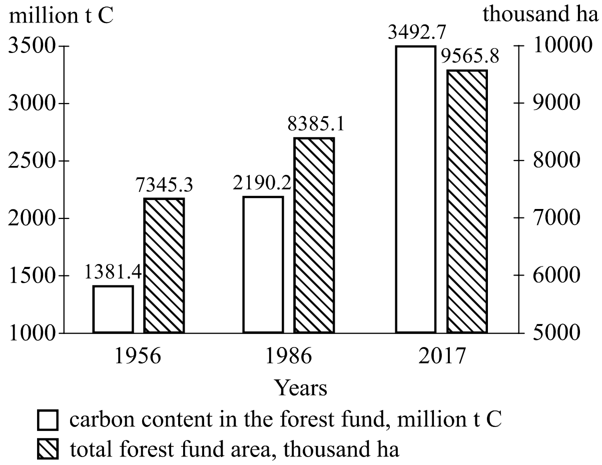

Figure 1. **Dynamics of carbon and the forest fund area in the Republic of Belarus**

First, we should mention a key permanent factor of measures to enhance forest productivity as the main strategic goal of the forest sector. This also improves the carbon sequestration capacity of forests. Conventional and new forestry operations are in place on the condition that they enhance forest productivity.

The list of the actions is quite long, they are too varied and form an integral part of all forestry activities. We will focus on certain results of such activities.

There was a monitoring of long-term (nearly 60 years) effect from the forestry measures on wood stock increment and annual carbon sequestration by the stands in Ivye experimental production forest district and Negoreloe experimental forestry district. During the monitoring a considerable increase of carbon sequestration capacity was registered. By methods of forest regeneration after final fellings the increase of carbon sequestration was established as follows: forest plantations – +140 tC/year, natural reforestation with assistance measures – +0.99 tC/year. Increase resulting from forest care activities comprised: restoration with subsequent forest plantation – +1.39 tC/year, improvement fellings – +1.18 tC/year.

Second, a current factor of great impact on carbon sequestration is the present age structure of forest and wood harvest volumes. The current age structure of forests is not the optimal one but is very conducive to wood increment and associated carbon sequestration. The present index of age structure of national forests is equal to 0.30; the optimal age structure has an index set to zero. Today medium-aged stands occupy 44.3% of the forested areas and are by 14.3% higher than the optimal share. Medium-aged stands are characterized by maximum current wood increment that favours current increase of carbon pool in Belarusian forests.

Third, the forest sector of Belarus experienced an extension of areas of forest group I accompanied by restricted wood harvest for the past three-four decades. At the same time, the share of commercial forests of group II was decreasing (1983 – 64%, 2015– 45.1%). Thus, as the total forest area was increasing over the period from 1944 to 2015 (+4075.8 thousand ha), the area of commercial forests decreased by 441.0 thousand ha. The reduction of the commercial forest area of group II and the allowable cut limitations imposed by the Cut Regulations brought about low intensity of forest utilization in Belarus as compared to other countries. Wood harvest volumes per unit of total volume comprised 9.7 and 13.0 m^3 per 1000 m^3 of total volumes in 2013 and 2016 respectively that is 1.4 times as little as in Poland, twice as little as in Austria and 3.8 times as little as in Finland.

The above mentioned factors have increased the values of annual total stock dynamics: 1983 – 20.0 million m^3, 2017 – 37.6 million m^3 (Table 10). Considerable changes in forest fund area are not predicted in the long-term perspective. The age structure of forest will remain non-optimal. The decreasing share of medium-aged stands will lead to significant reduction of wood volumes. The increasing share of mature forests will make it necessary to increase the allowable cuts regardless of the limitations prescribed by the new Forest Code (2015). Experts estimate that 57% of the available mature stands will be cut until 2050. 22% of the wood volume is exempt from final cuts for nature conservation purposes. Considerable wood volumes are hardly accessible. Mature stands in the zones of radioactive contamination with ^{137}Cs density over 15 Kukm^2 are regarded as wood harvest reserves and are subject to cut restrictions. Under these conditions total average stock dynamics will decrease to 15–17 million m^3 or 2.5 times as little as of 01.01.2017. This dynamics will cause the reduction of carbon dioxide absorption by forest fund so that specific compensatory measures will be required to maintain the values achieved in 2017.

4.2. Component structure of forest carbon resources in Belarus

The component structure of carbon accumulated in the Belarusian forest fund (3 492.7 million t – Figure 1) is determined by regional soil and climate conditions and tree species structure. A vitally important feature of carbon flows is the predominance of storage form of carbon cycle (Figure 2) aimed at sequestration of soil carbon by forests.

Nearly three quarters of forest carbon pool of Belarus are organic soil carbon (73.37%). Nearly two thirds of the carbon sequestered by swampy forests (1.64 billion tC) and swamps (0.5 billion tC) have been withdrawn from the biological cycle for long-term conservation.

Small biological cycle of the national forests involves 1340.5 million tC (38.38% of forest fund carbon). Phytomass carbon, deadwood carbon, forest floor carbon and carbon in the upper 10-cm soil layer ("conventionally mobile carbon") are involved in the most active biological cycle. The total carbon volume is estimated at 1 073.9 million t. The remaining carbon amount (in 10–30 cm soil layer) belongs to the "conventionally stable" biocycle.

Another specific feature of biocycle and net flows of carbon "stock-emission" in the forest ecosystem of Belarus is the excess of total photosynthesis of forest vegetation over plant respiration and phytodetritus decomposition ("soil respiration"). This fact can be confirmed by the dynamics of carbon stock sequestered by the forest fund within the permanent boundaries, i.e., without account of lands transferred to the forest fund. For the last six decades the carbon content within the conventionally permanent forest fund area has increased as follows: +567 million tC in phytomass and +780 million tC in soil. Thus, we can observe accelerated carbon synthesis by forest phytomass and decelerated rate of "soil respiration". Both processes assist in absorption of carbon dioxide from the atmosphere.

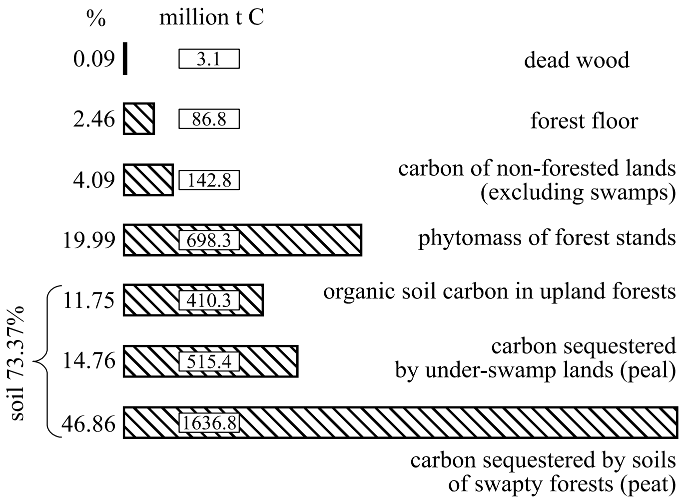

Figure 2. **Component structure of carbon budget of the forest fund areas in Belarus**

Forest growth conditions (forest type, type of forest growth conditions) are a determining factor for a component structure of forest carbon resources. The table below illustrates the analysis of the general forest carbon pool of Belarus (as of 2010) in terms of phytomass productivity of various series (groups) of forest types (Table 11).

The first rows of the Table list the following forest type series with higher carbon sequestration productivity (93.5–78.2 tC/ha) in a descending order: sorrel – bracken – myrtillus – mossy – urticaceous – vaccinium. The lower rows list the following forest type series possessing carbon sequestration productivity of 56.5–40.2 tC/ha (1.7–1.9 times less): riverine-grassy – long-mossy – ledum – sedge. The sphagnum series ranks last as it possesses extremely low carbon sequestration productivity of 15.3 tC/ha. The carbon sequestration productivity of other forest types is 72.3–58.6 tC/ha.

Table 11

Comparative carbon sequestration productivity of Belarusian forest stands in various forest type series (as of 2010)

Forest type series	Forested lands, ha	Total wood volume, million m^3	Carbon sequestration, tC/ha							
			ecosystem total	including by components:						carbon in the biological carbon sphere
				phytomass	phytodetritus	organic carbon of soil				
						total	mobile carbon	stable carbon in the layer thicker than 30 cm	peat depth, cm	
Heather	323 951	56,8	92,1	67,4	9,4	15,3	15,3	–	–	92,1
Vaccinium	36 904	7,6	105,9	78,2	11,1	16,6	16,6	–	–	105,9
Mossy	2 163 794	452,47	119,2	80,1	11,2	27,9	27,9	–	–	119,2
Bracken	895 280	202,7	134,9	86,6	12,2	36,1	36,1	–	–	134,9
Sorrel	1 179 078	287,8	160,9	93,5	13,1	54,3	54,3	–	–	160,9
Myrtillus	1 219 679	259,4	170,8	81,6	11,4	77,9	77,9	–	–	170,8
Ashweed	254 734	48,6	207,6	72,3	10,3	207,6	207,6	–	–	207,6
Urticaceous	146 705	30,4	768,5	79,3	11,2	678,0	489,4	188,6	90	579,9
Ferny	517 722	86,1	907,2	63,3	9,0	834,9	228,8	606,1	100	301,1
Riverine-grassy	79 146	11,3	563,9	56,5	7,8	499,6	262,4	237,2	50	326,7
Grass-floodplain	12 730	2,2	263,2	66,8	9,2	187,2	66,7	120,5	50	142,7
Meadowsweet	215 981	33,4	1 074,4	58,6	8,4	1 007,4	235,1	772,3	120	302,1
Sedge	458 716	49,5	1 268,1	40,9	5,9	1 221,3	235,1	986,2	150	281,9
Long-mossy (mineral)	241 980	35,5	566,3	56,1	7,9	502,3	261,5	240,8	50	325,5
Long-mossy (swampy)	177 762	18,6	789,1	40,2	5,7	743,2	261,5	481,7	80	307,4
Ledum	110 938	13,9	1 299,0	48,2	6,8	1 244,0	274,4	969,6	130	329,4
Sphagnum	10 800	0,43	1 391,2	15,3	2,4	1 373,5	254,2	1119,3	160	271,9
Total:	**8 045 900**	**1 596,7**	**341,0**	**75,9**	**10,7**	**254,4**	**99,7**	**154,7**	–	**186,3**

In view of this, we could expect the same dependencies of carbon sequestration by all components of forest ecosystems. However, we can observe rather opposite situation, i.e., upland forests deposit considerably smaller amounts of carbon than swampy forests. This can be explained by several reasons, to include: higher timber harvest intensity in upland forests, coarser texture and higher absorption capacity of soils in swampy forests. These factors lead to rapid mineralization of organic waste and higher biocycle intensity in upland forests. The biocycle of swampy forests is rather slow, the organic waste is conserved and deposited as soil humus and peat.

Carbon sequestration is largely influenced by forest growth conditions (Figure 3).

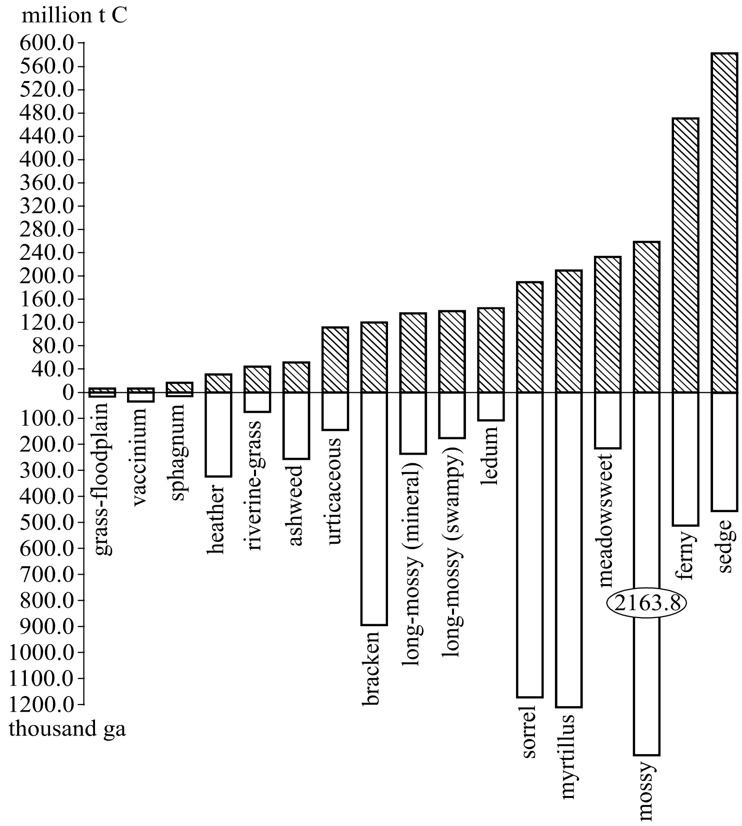

Figure 3. **Carbon sequestration by forested lands across forest type series**

The largest carbon volumes are sequestered by swampy forests (sedge, ferny, meadowsweet, ledum, long-mossy forest type series). The upland forests (heather, ashweed, bracken, sorrel, myrtillus, mossy) occupy 75% of the total forest areas. However they deposit only 31.3% of carbon. Long-mossy, ledum, meadowsweet, ferny and sedge forests, which cover only 21.4% of the total forest areas, have deposited 61.2% of the total carbon amount in the forest ecosystems of Belarus.

Main carbon reserves are deposited in forest stands soils. The total volume of carbon reserves in the forest ecosystem of Belarus is 2.74 billion tC with organic soil carbon making 74.6% of the total carbon volume. Stable soil carbon (peat) amounts to 60.8% of sol carbon, the other 39.8% is mobile carbon in the upper 30-cm soil layer (Figure 4). The phytomass carbon makes 22.3% and phytodetritus carbon – 3.1% of the total carbon sequestered by forests.

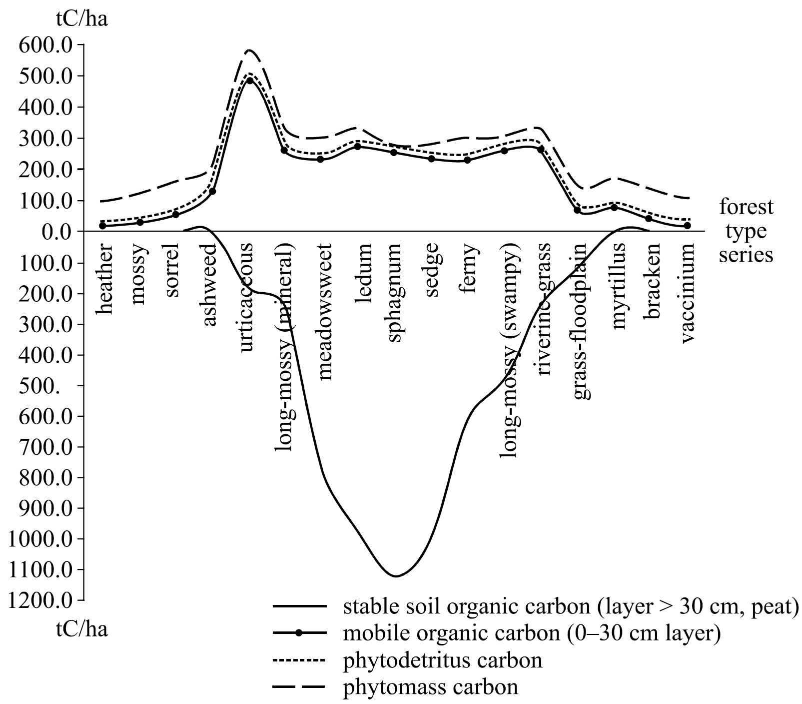

Figure 4. **Carbon sequestration by forest stands under various forest growth conditions**

The largest carbon volumes are deposited in swampy forest soils: from 1373.5 tC/ha in sphagnum forests to 499.6 tC/ha in riverine-grass forests; 187.2 tC/ha in grassy-floodplain forests. The upland forests have much smaller carbon sequestration capacity: from 15.3 tC/ha in heather forests to 207.6 tC/ha of organic carbon in ashweed forest soils.

The carbon deposited in upland forests is mobile, therefore it is directly and completely included in the biological cycle. In swampy forests (peat depth ≥ 50 cm) part of the organic carbon is not included in the biological cycle. Moreover, the biological cycle intensity is rather low. The biocycle does not involve a considerable amount of stable carbon (peat) deposited in the forest ecosystem.

For instance, the share of the carbon outside the biocycle in the following forest type series is: sphagnum – 80.5%, sedge – 77.8%, ledum – 74.6%, meadowsweet – 71.2%, ferny – 66.8%, etc. In view of this, low-intensity forest management is advised for swampy forests in order to prevent increased carbon emissions. The conservation function of atmospheric carbon stock in swampy forests is more significant than minor economic benefits from harvesting activity.

4.3. Swampy forests of Belarus in terms of carbon sequestration

Swampy forests are a focus of much attention of scientists and general public as they represent a unique ecological system with rich flora resources and biological diversity. They are a huge natural freshwater filter and an important element of carbon sequestration.

The role of swampy forests in Belarus becomes very essential under the conditions of large-scale draining activities performed on 75% of natural swamps and forested wetlands. This affects hydrological regime of the total area of the country. Increased road construction in the Belarusian forest fund improves accessibility of swampy forest resources. The intensive use of swampy forests can result in degraded biological diversity and carbon flow balance (“emission-stock”) in the areas.

By UNEP classification, swampy forests are moderate and northern forests of freshwater swamps, i.e., forests growing on swampy areas in the regions of moderate and cold climate. Boggy soils are typical of such forest types.

Swampy forests of Belarus occupy 1730.5 thousand ha of forested lands with the wood volume of 245.83 million m^3. Lowland-type swampy forests (82.7%) prevail, including such forest type series as ferny (29.95%), meadowsweet and urticaceous. Long-mossy type series (swampy forests) of transition bogs occupies a considerable area (10.3% of the total area of swampy forests).

Pine formation of swampy forests covers 1.9% of the forested lands whereas birch (39.4%) and black alder (34.5%) formations are predominant ones. The average growth class of swampy forests is 2.8, the average density is 0.63. Young growth occupy 22.3%, middle-aged – 17.8%, mature and overmature – 16.1% of the forested lands. The average wood volume per 1 ha of swampy forests is 142 m^3, including spruce forests – 189 m^3, black alder forests – 158 m^3, birch forests – 189 m^3, pine forests – 91 m^3 per 1 ha.

The impact of swampy forests on the water balance of the area, including water protection and water regulation functions is rather debatable. There are different views on feasibility or avoidance of forest hydromelioration of the forest fund lands. The debates result from ambiguous assessments of drainage melioration of forests and swamps in Russian Nonblack Soil Zone and Belarusian Polesye.

One of the viewpoints is based on the idea of swamps and wetlands as freshwater accumulators, regulators of river flows and river feeding that maintain high water content. Therefore, large-scale drainage of swamps and other wetlands, including boggy forests, aggravates hydrological regime of rivers and causes them to go low.

Another viewpoint says that swamps reduce the water content in rivers and swamp drainage leads to increasing the total and drought flows. It states that “virtually swamps cannot be seen as regulators of river feeding and have a reverse effect”. Large-scale drainage of swamps, boggy forests and meadows causes local shallowing of streams and small rivers due to the decreased level of underground waters in the area of drainage facilities. It also has very minor effect on the water content of large rivers.

It is worth mentioning another function of swampy forests as a source of atmospheric carbon dioxide sequestration. The Paris Agreement, contrary to the Kyoto Protocol, acknowledges that reduction of carbon dioxide emissions and absorption by forest ecosystems is a determining factor of climate change mitigation. The Paris Agreement seeks to promote the developing countries in forest regeneration and allowable cuts control. Still it is not quite clear why only the developing countries should be a focus of attention. Does it mean other countries may allow reforestation and forest degradation? Below we will consider the role of swampy forests as an accumulating link in the carbon dioxide "stock-emission" balance in the light of the Paris Agreement.

Table 12 illustrates the carbon budget of swampy forests. Main carbon reserves (93.9%) are deposited in soils of swampy forests. The share of phytomass carbon is only 5.6% of the carbon pool of swampy forests. Small biological cycle involves only 32% of the carbon reserves of swampy forests (phytomass + dead wood + forest floor + organic carbon of the upper 30-cm soil layer). It should be noted that upland forests have all of their carbon deposits (100%) concentrated in the exchange zone (cycle) between living and non-living components of the forest ecosystem. Conservation of atmospheric carbon in the shape of peat (approx. 1.2 billion tC or 68% of its total reserves on forested lands) is a major function of Belarusian swampy forests.

Comparative productivity of national forests by wood volumes and carbon reserves (Figure 5) shows that forest carbon pool (2843.6 million t C, incl. dead wood and forest floor) comprises 63.6% of forest swampy pool. The carbon deposited by swampy forests of the country makes 43.2%.

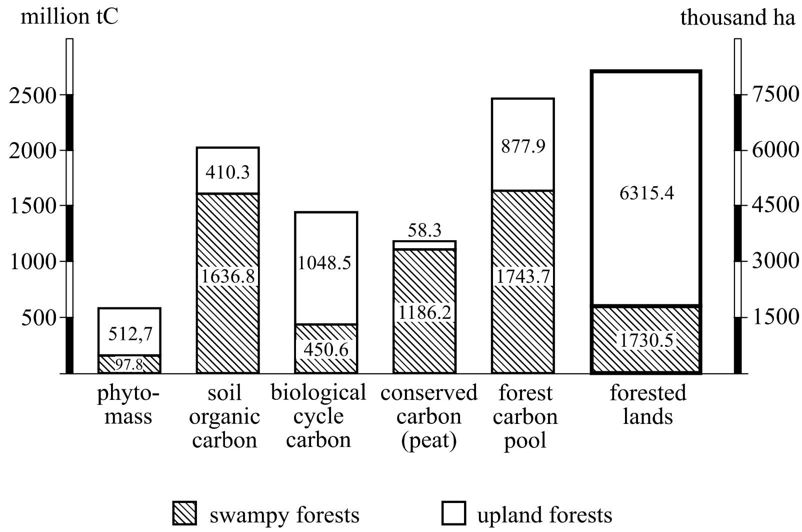

Figure 5. **Comparative carbon budget of Belarusian forests, including swampy forests and upland forests (forested lands)**

Table 12

Carbon reserves in swampy forests of Belarus, thousand t (forested lands)

Forest type series	Phytomass			Dead wood	Forest floor	Soil organic carbon				Swampy forest carbon pool
	overground	underground	total			mobile	stable	conserved (peat)	total	
Sphagnum	146	90	236	6	12	915	1 830	12 088	14 833	15 087
Long-mossy (swampy forests)	6 293	1 172	7 465	230	634	15 495	30 990	85 624	132 109	140 438
Ledum	4 698	815	5 513	185	392	10 147	20 294	107 567	138 008	144 098
Sedge	16 500	3 140	19 640	620	948	35 948	72 346	452 364	560 658	581 866
Meadowsweet	11 136	2 070	13 206	375	724	16 927	33 850	166 803	217 580	231 885
Riverine-grass	3 795	715	4 510	124	282	6 923	13 845	18 773	39 541	44 457
Grass-floodplain	749	147	896	27	55	283	566	1534	2383	3361
Ferny	28 822	5 259	34 081	1 064	2 276	39 485	78 970	313 817	432 272	469 693
Urticaceous	10 238	2 014	12 252	354	815	23 932	47 865	27 662	99 419	112 840
Total	82 377	15 422	97 799	2 985	6 138	150 055	300 556	1 186 192	1 636 803	1 743 725

Small biological cycle of national forests involves 1499.1 million tC (54.6% of the forest carbon deposits). 450.6 tC in the soil upper layer (≤30 cm) is immediate reserve of soil organic carbon to be involved in biocycle under accelerated mineralization of soil humus, e.g., after forest drainage or forest cuts, etc. Therefore, we recommend a low-intensity forest management because the emission then would include carbon of phytomass, detritus and soil upper layer.

Swampy forests have accumulated considerable wood volumes (245.83 million m^3). Timber harvest is impeded by low transport accessibility. The cost effectiveness of forest growing is very low or even negative in undrained pine forests of upland swamps and soft-leaved stands of transition and low-land swamps. Such swampy forests occupy about 775 of the total area. At the same time the cost of the sequestered carbon of forest swampy ecosystem is 2.5 times as high as the cost of wood volumes of the swampy forests.

Swampy forests that are not cost-efficient in terms of timber harvest (about 1.3 million ha) can generate an annual income of 47 million USD by selling carbon quotas of the current increment. This will also promote conservation of biodiversity of swampy forests. Such approach towards forest management of swampy forests of Belarus can engage international environmental funds and facilitate the access to international markets of free carbon quotas.

4.4. Estimation of carbon dioxide absorption by the Belarusian forest fund

4.4.1. Estimation of wood stock and carbon dioxide absorption level in terms of conventional forestry practices

Implementation of conventional and not completely performed actions on increasing the wood productivity allows for the following dynamics of wood volumes in the Republic of Belarus (Table 13).

The dynamics of the forest stands depends on allowable cuts, i.e., cutting operations in mature stands. The estimation (Table 13) uses the concept of timber cutting fund (share of the cut volumes of mature stands in the available stands) as equal to 57% for 2016–2050. The true necessity to conserve 43% of mature stands consists in the following.

Data of the National Forest Cadastre of the Republic of Belarus of 01.01.2015 show that 57.5 million m^3 of mature stands out of the total mature stands volume (263.0 million m^3) were not allowed for forest cuts. Therefore, 22% of estimated volume of the timber cutting fund was exempt from final fellings for conservation reasons (protected nature areas, conservation forest sites). The share of such forest category will increase. Moreover, large volumes of wood stock are hardly accessible. Mature stands in contamination areas having 137Cs density of 15-40 Ku/km^2 are regarded as timber cutting reserve.

Table 13

Estimated areas and volumes of forest stands of the Republic of Belarus

Predominant tree species	Area, thousand ha			Volume, million m^3			Average stock, m^3/ha		
	Years								
	2015	2030	2050	2015	2030	2050	2015	2030	2050
Pine	4129	4600	5590	955	1155	1425	231	244	255
Spruce	759	900	800	190	207	184	250	225	230
Other coniferous	1	100	120	0,1	10	13	98	100	110
Oak	281	400	500	50	72	93	178	151	185
Other hard-leaved	49	80	100	8	14	18	171	281	180
Birch	1899	1605	1275	319	276	223	168	157	175
Aspen	174	150	100	34	35	23	197	173	230
Grey alder	161	130	100	23	20	15	141	142	150
Black alder	697	700	700	132	126	126	189	147	180
Other soft-leaved	54	55	55	3	4	5	53	63	90
Total	8204	8720	9340	1714	1917	2125	209	220	227
Forest cover, %	39,4	41,9	44,9						

We assume that the 57% value is truly advisable for the timber cutting fund.

Table 14 gives estimation and dynamics of atmospheric carbon dioxide absorption by forest stands of the Republic of Belarus for 2015 – 2030–2050.

The estimation (Table 14) proves positive dynamics of carbon absorption by the forest fund lands of the Republic of Belarus until 2050. Average annual sequestration will amount to 0.66 tC/ha·year in 2015–2030 in terms of one hectare of forest fund lands and 0.48 tC/ha·year in 2031–2050 with 0.54 tC/ha·year in 2016–2030 collectively. As compared to the period of 1960–2010, the annual carbon sequestration by forest fund lands will apparently double reduce. This can be judged by the current age structure of the Belarusian forests.

Table 14

Estimation of carbon sequestration dynamics in the forest stands until 2050

Forest stand components and forest land types	Carbon content in the record year, million tC		
	2015	2030	2050
Standing wood	596,5	665,4	738,5
Young growth and undergrowth	0,9	1,0	1,0
Live forest cover	8,6	9,6	10,1
Roots	81,4	90,8	100,6
Windfallen and dry standing wood	3,2	3,6	4,0
Forest floor	89,5	100,1	110,9
Total forest stands (forested lands)	780,1	870,5	965,1
Non-forested lands (vegetation)	135,0	133,0	130,0
Total forest lands (vegetation)	915,1	1003,5	1095,1
Organic carbon of the 30-cm upper layer of soils of forest fund lands	2189,9	2200,5	2209,9
Total pool of forest fund lands	3105,0	3204,0	3305,0

The past post-war period (1944–2015) was characterized by large-scale forest growing, predominance of young growth with relatively low average wood stock. For the estimated (2016–2030) period the age structure of Belarusian forests has reversed, i.e., ripening and mature stands created in the post-war years are prevailing. They have large average wood stock per a unit area. This fact resulted in increased carbon sequestration in the forest fund over 1944–2015 amounting to approx. 0.9 billion tC with the annual carbon increment of average 1.58 tC/ha·year.

The estimated period will experience increase in allowable cuts because of the considerable increment in mature stands, i.e., in 2015 – 263 million m^3, estimation for 2050 – 1442 million m^3 (in case mature stands are not cut). Forests perform multiple functions, including social, environmental and wood-forming. Forests are to be cut for timber harvest to allowable extent. Rational forest management principles do not allow cuts in ripening stands, neither they recommend to preserve overmature stands. The allowable cuts must be within the limits of annual wood increment.

Estimated allowable cut envisages felling of mature stands to the amount of 982 million m^3. The cut areas will be subject to forest regeneration. The total volume of young growth on the regenerated cut areas will amount to approx. 230 million m^3 over the estimated period.

The difference between the cut and the regenerated volumes will make approx. 752 million m^3 over 2016–2050. The resulting loss in wood stock will be partially compensated by middle-aged and ripening forest stands which were not affected by intermediate cuts. However, we will observe reduced annual carbon sequestration by the forest fund areas in 2016–2050 as compared to the past periods (1944–2015, 1960–2015, 1990–2015, etc.). The positive value of annual carbon sequestration will be maintained. Therefore, over 2016–2050 we will observe atmospheric carbon "stock" in the forest fund lands of the Republic of Belarus.

Further, we will touch upon the units of carbon dioxide absorption which can be expected in the "stock-emission" system of greenhouse gases in the near future (Table 15).

Table 15

Estimation of carbon dioxide absorption by forest fund lands of the Republic of Belarus until 2050

Carbon pools	Absorption of atmospheric carbon dioxide by periods, million t CO_2			Average annual sequestration (absorption) of atmospheric carbon dioxide by periods, tCO_2/year		
	2016–2030	2031–2050	2016–2050	2016–2030	2031–2050	2016–2050
1. Forest fund lands	363	370	733	24	18	21
2. Phytomass of forested lands	331	347	678	22	17	19
3. Phytomass of stemwood	252	268	520	17	13	15

Carbon dioxide absorption is by 92% ensured by phytomass of forested lands, primarily through the formation of stemwood (71% of the CO_2 absorption by forest fund lands). It is expected to compensate the industrial greenhouse gases emissions to the annual amount of 18–24 t CO_2 through carbon dioxide absorption by forest fund lands. Stands volume is the most accurately recorded unit by the national forest fund. Therefore it is suggested to adopt annual carbon dioxide sequestration by stemwood as a unit of greenhouse gases absorption. For the near future it is recommended to estimate greenhouse gases absorption by the forest fund lands through annual increment of forest stands to the amount of 17 million t CO_2 in 2016–2030 and 15 million t CO_2 in 2031–2050.

4.4.2 Estimation of carbon dioxide absorption by the Belarusian forest fund until 2030 in terms of the planned wood harvest volumes

Over 1956–2017 forests of Belarus absorbed about 2 111 million t of carbon from the atmosphere and deposited it in the phytomass and soil of forest fund lands (Figure 1). This amount corresponds to the "stock" (emission) of approx. 7 740 million t CO_2. Taking into account that the increment of CO_2 weight ("emission") in the earth atmosphere amounted to nearly 420 billion t, the sustainable carbon sequestration capacity of the Belarusian forests should be highly appreciated.

A key factor of increasing the carbon dioxide absorption is improved forest productivity resulting from relevant forestry actions. The following action are considered to be efficient in terms of enhancing the carbon sequestration capacity of forests: reduced periods of forest regeneration on non-forested lands (cut areas, burn-out areas, etc.) to 2–3 years; creation of forest plantations by large-sized planting material, closed-root system planting material with improved gene characteristics; timely agrotechnical tending, pests and disease control in open forest plantations; development of open forest plantations into closed ones over the period of max. 6–7 years; expansion of operating fund areas intended for partial main cuts with a focus on natural forest regeneration of target (main) tree species and reduced cutting cycle to 5–7 years or more; implementation of environmentally safe technology with preservation of young growth; necessary measures to be taken upon gradual cuts to achieve normal density (1.0) of the young growth preserved; biological amelioration (bean family plants, other biomeliorants) during creation of forest plantations and young growth of natural and man-made origin; selection of main tree species and targeted structure of forest stands based on soil-typological forest growth conditions; restoration of low-grade and low-density young forests and middle-aged stands; adherence to the improvement cutting rates. There are also opportunities for increasing the forest cover of Belarus.

The information below outlines provisions for maintaining and increasing the carbon dioxide absorption by forests under efficient forest management. The outcomes of forestry actions taken over a long period (Ivye experimental and production forestry station, Negoreloye forestry experimental station), planning of forestry actions for the auditing period (Osipovichi experimental forestry enterprise, Bykhov and Cherikov forestry enterprises) and mid-term estimation of carbon pools dynamics (forest fund of the Republic of Belarus and Brest SPFA) show that carbon dioxide emission is surpassed by the absorption under the conditions of sustainable forest management and implementation of environmentally sound and cost-effective measures on forest growing and protection (Table 16).

Table 16

Average annual increment of carbon dioxide absorption resulting from efficient forestry actions

Forest fund entity	Area (forested lands), thousand ha	Period, years	Increment in carbon dioxide absorption, t CO_2/ha · year
1. Ivye experimental and production forestry station, Negoreloye forestry experimental station	13,673	1946–2008	+2,56
2. Osipovichi experimental forestry enterprise, Bykhov and Cherikov forestry enterprises	278,261	2014–2023	+0,63
3. Brest SPFA	1068,7	2013–2033	+0,49
4. Forests of the Republic of Belarus	8068,7	2011–2030	+1,10

The forestry measures promote carbon sequestration capacity of forests. The forest regeneration methods result in the following increment in carbon absorption: creation of forest plantations – +1.40 t CO_2/ha · year; natural regeneration with assistance measures – +0.99 t CO_2/ha · year. The corresponding increment resulting from forest care actions amounts to: +1.39 t CO_2/ha · year from restoration actions with subsequent forest planting; +1.28 t CO_2/ha · year from reconstruction cuts; +1.18 t CO_2/ha · year from improvement cuts (Table 17). Implementation of the above forestry measures makes it possible to achieve 50% increase incarbon sequestration capacity of a forest stand with the cost-effectiveness of 18% and higher (Table 18).

The forest sector of Belarus should be given credit for large-scale carbon sequestration by phytomass and forest fund soils (figure 6). The same level of carbon dioxide absorption must be maintained and, if possible, increased in future as this is a key factor of CO_2 removal from the atmosphere. This becomes one of the major goals of the Belarusian forest sector due to the aggravating weather and climate change resulting from greenhouse gases emissions. Contribution of the forest sector to climate mitigation will be assessed by the increment of annual carbon dioxide absorption by the forest fund.

Table 17

Efficiency of long-term forestry impact on carbon sequestration

Measures	Scope of measure, ha	The resulting increment over 57–58 years	
		Wood stock, m^3/ha	Carbon sequestration, t C/ha
1. Creation of forest plantations upon final cuts	698,5	+115	+44
2. Measures of assistance to natural forest regeneration upon final cuts	385,8	+54	+21
3. Reconstruction cuts	187,1	+97	+37
4. Restoration by forest plantations	86,8	+114	+44
5. Improvement cuts	198,2	+84	+32

Table 18

Estimated carbon sequestration effect from targeted forestry measures

Measures	Income over 57–58 years, million BYN	Implementation costs of measure, million BYN	Effect from measures		
			Total, million BYN	Including	
				million BYN/ha	BYN/BYN costs
1. Creation of forest plantations upon final cuts	4526,40	3250,10	1276,30	1,83	1,40
2. Measures of assistance to natural forest regeneration upon final cuts	1172,80	79,86	1092,94	2,84	14,69
3. Reconstruction cuts	1025,20	516,40	508,80	2,72	1,99
4. Restoration by forest plantations	555,60	471,14	85,46	0,99	1,18
5. Improvement cuts	919,60	266,78	652,82	3,30	3,45

Average periodical (1956–2017) annual carbon dioxide absorption by the forest fund is estimated at 10.64 tCO_2/year. During certain periods the value of annual absorption varied from 3.8 to 14.4 tCO_2/year that can be attributed to the transfer of lands to the forest fund, wood harvest volumes, forest regeneration and forest growing.

In 2005 Belarus acceded to the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC). The first National Communication on the UNFCCC commitment of Belarus introduced the amount of greenhouse gases emissions. In 2011 the guidance document “Evaluation technique for total and annual carbon sequestration by forests of the Republic of Belarus” was approved and made effective by the order of the Ministry of Forestry of the Republic of Belarus No.81 dated 28.03.2011. From that time onward the record of carbon content in the forest fund has been kept in the Forest Cadastre and forest inventory projects.

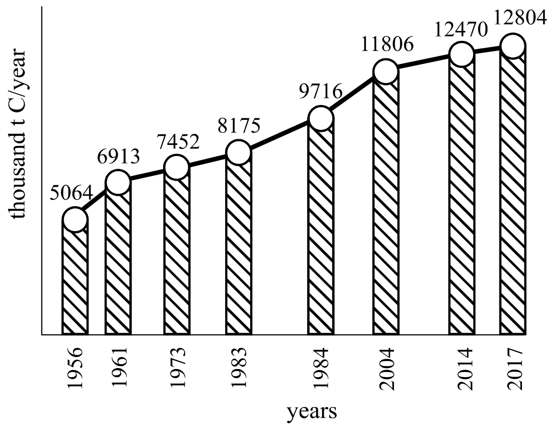

Figure 6. **Total dynamics of carbon sequestnation by the forest fund of Belarus**

Over the past 10-15 years the transfer of lands has been rather small-scale and the forest fund area has not changed considerably. For this reason the basic value of annual carbon dioxide absorption by forest fund should be set to 4.91 t CO_2/year. This value has been established as average periodical for 2000–2017 and remained unchanged even after the sweeping windblow in 2016. The emergency forest damage of 2016 proved the sustainability of the national forest sector in maintaining high level of annual carbon dioxide absorption at 46986 thousand t of atmospheric carbon dioxide.

Carbon balance of the forest fund is not time-stable due to the dynamics of wood stock and the level of forest utilization. Carbon budget can be altered by the following factors: reduced areas of forested lands, changing age structure of forests due to increasing areas of mature and ripening stands, increased wood harvest by final fellings, regeneration cuts, conversion and other cuts. These factors are also able to redirect the net flow of carbon into the atmosphere. Carbon flow monitoring and mechanism of their calculation are important tasks of the forest sector. Predominating “emission” in the carbon balance of the Belarusian forest ecosystem can adversely affect the national forest sector under the conditions of globally rising pressure in the field of carbon dioxide emission into the atmosphere.

Sustainable and dynamic development of forestry in the Republic of Belarus creates good conditions for maintaining the same dynamics of forest fund (Table 10) both in the short-term (until 2030) and long-term (until 2050) prospects. Whereas the total area of the forest fund will remain unchanged (9 565.8 thousand ha), the forested lands are predicted to increase until 2030 (+80.6 thousand ha) with the total wood increment of 47.4 million m^3. Steady wood harvest volumes can ensure stabilized carbon budget in the forests of Belarus (Table 19, Figure 7).

Table 19

Carbon budget of the forest fund in the Republic of Belarus as of 01.01.2017

No.	Carbon budget indicators	Value
1	Total carbon of the forest fund, million tC	3492.7
2	Phytomass carbon of the forest fund, million tC	698.3
3	Dead phytomass carbon of the forest fund, million tC	89.1
4	Organic soil carbon of the forest fund, million tC	2705.3
5	Average carbon sequestration by the forest fund, tC/ha	365
6	Total change in carbon sequestration by the forest fund, thousand tC/year	12804
7	Average change in carbon sequestration by the forest fund, tC/ha/year	1.61
8	Annual carbon dioxide absorption by the forest fund, tCO_2/year	46 986

The stock of atmospheric carbon mainly occurs in the forest stands under the Ministry of Forestry (Figure 7). They occupy 88% of the total forest fund area and are responsible for 90.63% of the annual level of carbon dioxide absorption by the Belarusian forests.

Therefore, sustainability of carbon sequestration by national forests is dependent on the decision-making by the principal forest fund owner. It should be taken into account that the current age structure of forests is moving towards the mature ones, the allowable cut volumes are being increased and the demand for wood resources is growing on the domestic market. The listed factors can result in the decrease of carbon dioxide absorption by forests. Wood harvest volumes should be given special focus here.

The wood harvest in the Belarusian forests is predicted to enlarge. Improvement fellings have been excluded when calculating the carbon flows from intermediate cuttings. Trees to be cut for thinning are selected from the trees that are likely to naturally die. Such measures do not affect the level of carbon dioxide absorption. On the contrary, timber transportation after final felling, regeneration cuts, conversion and other cuts is regarded as the process of "instant wood oxidation" associated with the carbon dioxide emission.

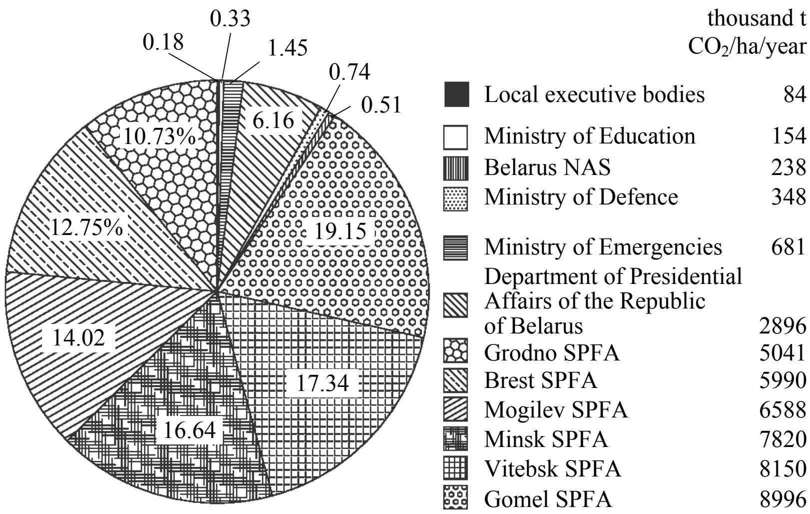

Figure 7. **Annual CO_2 absorption by the forest fund under the ownership of governmental bodies and other agencies**

Table 20 outlines the predictable annual wood harvest and timber transportation until 2030.

Table 20

Predictable wood harvest thousand m^3/year

Governmental bodies and other agencies	Volume
2018	
Republic of Belarus	13476.6
Ministry of Forestry including: Brest SPFA	12670.8 1311.0
Vitebsk SPFA	2678.7
Gomel SPFA	2904.9
Grodno SPFA	1065.3
Minsk SPFA	2558.5
Mogilev SPFA	2152.4
Department of Presidential Affairs of the Republic of Belarus	573.8
Ministry of Defense	74.9
Ministry of Education	73.2
Belarus NAS	83.9
2025	
Republic of Belarus	15178.8
Ministry of Forestry including: Brest SPFA	14287.9 1947.8
Vitebsk SPFA	2814.6
Gomel SPFA	2982.3
Grodno SPFA	1984.6
Minsk SPFA	2786.9
Mogilev SPFA	2371.7
Department of Presidential Affairs of the Republic of Belarus	644.1
Ministry of Defense	87.6
Ministry of Education	71.9
Belarus NAS	87.3
2030	
Republic of Belarus	19058.2
Ministry of Forestry including: Brest SPFA	17945.7 1991.7
Vitebsk SPFA	4659.9
Gomel SPFA	3196.2
Grodno SPFA	2447.8
Minsk SPFA	3244.3
Mogilev SPFA	2405.8
Department of Presidential Affairs of the Republic of Belarus	798.4
Ministry of Defense	160.0
Ministry of Education	66.8
Belarus NAS	87.3

Wood harvest is estimated to increase by average 1694 thousand m^3 until 2030 as compared to 2017. Consequently the level of annual carbon dioxide absorption is expected to decrease by average 1708 thousand t annually (Table 21).

Table 21

Estimated decrease of carbon stock and increase of carbon dioxide "emission" in the forest fund of the Republic of Belarus due to increased wood harvest volumes

Governmental bodies and other agencies	Carbon removal through wood harvest, thousand tC		Carbon dioxide "emission" from wood harvest and transportation, thousand tCO_2		
	2018–2025	2026–2030	2018–2025	2026–2030	Total 2018–2030
Republic of Belarus	2148	4375	7874	16038	23912
Ministry of Forestry including:	2035	4107	7460	15056	22516
Brest SPFA	810	840	2970	3079	6049
Vitebsk SPFA	170	1416	623	5191	5814
Gomel SPFA	100	249	367	913	1280
Grodno SPFA	398	715	1459	2621	4080
Minsk SPFA	283	590	1037	2163	3200
Mogilev SPFA	274	297	1004	1089	2093
Department of Presidential Affairs of the Republic of Belarus	89	195	326	715	1041
Ministry of Defense	16	65	59	238	297
Ministry of Education	3	3	11	11	22
Belarus NAS	5	5	18	18	36

The declining tendency of carbon stock contradicts the national policy in the field of climate change mitigation. The forest sector must compensate the CO_2 emissions from wood harvest by means of measures to increase the carbon sequestration capacity of forests. In this way, the present level of the carbon dioxide absorption will be maintained. Responsible forest management and efficient actions that can affect carbon flows can increase the level of carbon dioxide absorption by the forest fund of Belarus.

5

EFFECT OF THE AGE STRUCTURE ON THE CARBON DIOXIDE ABSORPTION BY FORESTS

Nowadays climate change has become a globally known problem. This can be attributed to the increased amount of carbon dioxide in the atmosphere of our planet [42, 54, 55, 75, 6, 100, 101, 114, 116]. According to the outcomes of the United Nations Conference on Sustainable Development Rio + 20 held in Brazil in 2012, solutions to the sustainable development problems should focus on “green” ideology and appropriate economy. The Conference resulted in the Declaration “The Future We Want”. The key provisions of the document say that ongoing well-being can only be ensured by the principles of “green” economy. Its formation and expansion are within the context of addressing priority social and economic issues, including employment and people’s quality of life. According to United Nations Environmental Programme, “green” economy improves the well-being of people, ensures social equity and considerably reduces environmental risks [91].

Among the most important documents adopted by the United Nations Conference on Environment & Development, Rio de Janeiro, 1992, there is the Framework Convention on Climate Change [91].

The obligations taken by the Republic of Belarus within the UN Framework Convention on Climate Change as defined for countries listed in Appendix 1 to the Convention include greenhouse gases inventory and assessment of their contribution to the global warming effect together with the preparation of detailed information about potential climate change effect on forest ecosystems and assessment of climate change adaptation measures.

The Kyoto Protocol envisages positive balance between carbon emissions and absorption in line with the provisions listed above. According to the Kyoto Protocol the balance between carbon emissions and sequestration is to be globally improved. The Republic of Belarus has acceded to the protocol and ensures the fulfillment of its provisions [98].

The issues mentioned have been addressed by the world community several times over the past years. The conventions signed in Paris in 2016 set stricter criteria of the carbon emissions cuts. At the same time a number of industrialized countries (the USA, Germany, etc.) still have greenhouse gas emissions at a higher level that can be absorbed by the vegetation covering the areas of these countries. The Washington's stance on the problem showcases this fact as President Trump has refused to commit to the Paris Agreement.

Unlike the countries mentioned, the Republic of Belarus continues reducing greenhouse gas emissions and strongly concentrates on the carbon sequestration by the vegetative cover, especially forests. Therefore, the information about the stock and rate of carbon sequestration is becoming highly essential. The conventional application of the balance between carbon emissions and sequestration is one of the governing factors regulating atmosphere and climate. Moreover, this factor has become crucial for regulating economic activity as well.

Identification of the climate change consequences and related forecasts for the future of forest cover of Belarus (stands structure, productivity, resource capacity, etc.) are highly important for the forest sector in order to work out practical measures aimed at the climate change adaptation of the forest sector and related industries. Therefore, the dynamics of resource and environmental capacity of forest formations caused by climate change is of great scientific and applied value.

Key climate change aspects that have a considerable impact on forestry are as follows [91]:

– monthly average temperature increase throughout the year in the period from 2010 till 2039 by average 0.6–1.9°C and by 1.0–2.9°C in subsequent years;

– extended periods of mean daily temperatures above temperature ranges of 5 and 10°C and increased cumulative temperatures over relevant periods;

– lower soil freezing levels and decreased periods of soil freezing in winter;

– more frequent adverse weather conditions, i.e. draughts and frosts, especially in summer months in southern reclaimed regions of Belarus;

– lowered level of ground waters.

Climate changes of the first half of XXI century played a vital role for forest sector. Monthly average temperature increased throughout the year by average 0.6–2.9°C. This was accompanied by ongoing stands transpiration and slight increase in rainfall in winter months during which the rainfall is not a significant source of water for the current year vegetation.

Forests in Belarus are a highly important renewable resource. The forests occupy over 8.0 million hectares and have a total wood stock of more than 1.7 billion m^3. The national forest cover has been estimated as 39.5% [130].

The main wood species of the Belarusian forests is pine. It covers 56% of all forested lands [130]. Therefore, the choice of pine as a model wood species for carbon sequestration by forest stands has been justified.

Pine stands are quite evenly scattered over the territory of Belarus, however they are characterized by an uneven age structure. The age structure of the pine stands is prevailed by middle-aged stands. This fact can be attributed to mass fellings of war and post-war periods that continued until the 1960s. By 1991 the share of mature stands had decreased as low as 2.2% and 1.8% without account of bog stands [51, 53, 61, 82, 98, 122, 123]. Nowadays, the share of mature stands is dynamically increasing and has almost amounted to 11% [130]. The achieved share of mature stands demonstrates a good progression as compared to previous period, however is still half the scientific-based standards [43, 49, 51, 68].

Carbon sequestration studies earlier conducted by Belarusian scientists have made it possible to obtain an overview for Belarus, however, the studies need to be continued. Thus, it is necessary to obtain detailed data about carbon sequestration by pine stands of various ages in order to optimize age structure of pine forests.

Based on the foregoing, the choice of pine as a subject-matter of the study is justified and essential.

5.1. Work plan, methodology of the study, experimental material

The work plan has been set by the terms and conditions of the contract and is aimed at achieving the target of the project activity. The work plan covers the following areas.

1. Current state analysis.
2. Collection and analysis of experimental data.
3. Determination of carbon stock in pine stands by age classes.
4. Determination of current annual increment in Belarusian pine stands by age classes.
5. Determination of annual carbon sequestration value in pine stands by age classes.
6. Measures for increasing carbon sequestration by pine stands.
7. Forest maturity as a main indicator of age classification of stands.
8. Ecological maturity of forests.
9. Current optimum age classification of forests according to the existing felling ages.
10. Optimization of age structure of pine stands based on ecological maturity of forests.
11. Recommendations for improvement of age structure of pine stands in Belarus.

Methodology of the study has been adjusted to the target of the project activity and the issues which are to be addressed to achieve it. It is based on the methods commonly used in general biology, silviculture, forest taxation, economics and ecology that have been described in reference sources, specifications and guidelines [43, 44, 45, 48, 51, 82, 83, 84, 87, 91, 97, 99, 102, 103, 106, 112, 113, 122, 123, 195, 85, 115]. The Figure 8 below outlines the chart of collecting, processing and analyzing the study findings in accordance to the existing regulations [46]. The work will result in stands model and the amount of carbon sequestration.

The study also uses methods of biometry, mathematical modeling and system analysis [46, 56, 58, 59, 62, 63, 64, 65, 71, 72, 74, 76, 95, 119, 121]. The uses of system approach and mathematical modeling in forestry over the recent decades have been extensively highlighted in special literature and are described in numerous publications. The key related publications are monographs and papers by O.A. Atroshchenko [46], V.F. Baginskiy [51, 56, 115], S.A. Dyrenkov [65], V.V. Kuzmichev [104], A.K. Kiviste [74], A.I. Koltunova [76], K.E. Nikitin [94, 95], A.Z. Shvidenko [95] and other authors. The works of the mentioned and other scholars [109, 121] describe main functions of forest growth, including empirical and mixed ones. Many models have similar function graphs over certain time or other interval and, thus, can be interchangeable.

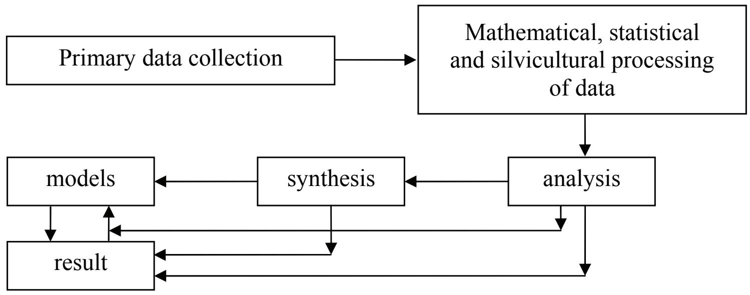

Figure 8. **Chart of data collecting and processing**

The analytical review of the current state of the problem is done by the review of official regulatory sources [60, 61, 72, 77, 81, 6, 89, 96, 121, 122, 123], other legal documents and reference sources listed as bibliography.

Forest inventory data taken from the Forest Cadastre as of 01.01.2017 and data from the updated Forest Fund Databank provided by RUE "Belgosles" serve as experimental material for this study.

The experimental materials are given below.

There are numerous publications dedicated to the study of climate change impacts on forest sector and forest ecosystems [101, 113]. Climate change evaluation in the territory of Belarus in the first half of the current century is based upon the atmosphere general circulation model hadCM2 (Great Britain). The reference time interval is 1960–1990.

The carbon stock can be evaluated by various methods, i.e., by sample plots or by forest inventory data on wood and phytomass growth and stock [42, 54, 57, 61, 62, 73, 6, 88, 101, 105, 108, 109, 114, 7, 116, 119]. The forest inventory data prove to be a time-saving and less expensive source of information and more accurate than sample plot data extrapolation beyond wood species, growth class, age class and density class [73, 7, 116, 117]. Therefore, in order to calculate carbon stock in wood and phytomass we have applied the method which has been several times tested out by other authors, i.e., we have relied upon the forest inventory data.

The carbon volume of the actual inventory and increment has been calculated by means of conversion factors. The factors can be very easily calculated having the chemical formula of the basic component of wood – cellulose. Besides cellulose wood is composed of lignin [53, 57]. The lignin is found in softwood as vanillin, in hardwood as syringaldehyde and vanillin. The carbon content of lignin is comparable with that of cellulose [54, 57, 75, 6, 93, 118].

The main regulatory document used for carbon volume calculation is a guidance document "Evaluation technique for total and annual carbon sequestration by forests of the Republic of Belarus" (by L.N. Rozhkov) [6] officially approved by the Ministry of Forestry of the Republic of Belarus. Conversion factors can differ for various age classes of pine stands due to the increasing density of wood as it matures. Average conversion factors are estimated as follows: age class 1 – 0.48; age class 2 – 0.49; age class 3 – 0.50; age class 4 – 0.505; age class 5 – 0.51; age class 6 and older – 0.515.

Therefore, to calculate the carbon volume sequestered by a stand we need to have the data about wood stock and its current increment as well as its specific density. An average weight of one cubic metre of absolutely-dry pinewood is 520 kg [77]. In a growing stand the specific density of wood depends on a tree species, age and forest type. The carbon share in the carbon dioxide sequestered by vegetation is 30.44%.

The main component to determine the volume of carbon sequestration is the carbon contained in stemwood. This value can be determined in the most accurate manner. The values of carbon sequestration in branches, roots and phytomass can easily be calculated with conversion factors given in the above mentioned guidance document "Evaluation technique for total and annual carbon sequestration by forests of the Republic of Belarus" [44].

The foregoing techniques for evaluation of carbon sequestration have previously been tested out by many experts [73, 88, 115, 7, 118] and ensure the best acceptable accuracy under both static and dynamic conditions.

A significant issue for this study is to determine wood stock and current increment of pine stands by age classes. While comprehensive data on wood stock and its current dynamics can be taken from the Forest Cadastre [130], the current increment has to be evaluated by scientific methods. The increment depends upon a tree species, age, growth conditions (growth rate) and density. The data of forest fund inventory allow us to obtain rather accurate information about the age and stock of the stands under study. The most complicated issue is the dependence of the current increment on the density. There is a lot of research related hereto [44, 45, 131]. Current increments depending on the age and growth rate are given in various yield tables. We use pine stands yield tables approved by the Ministry of Forestry of BSSR and Gosleskhoz (State Forestry Committee) of USSR in 1984 [96]. The average density data by age classes can be found in the Forest Fund Databank which was provided to us (chapter 1.3). The transfer from stand density 1.0 to the real stand density can be done according to the Gerhard formula [44, 45, 115]:

for shade-tolerant species:

$$Z_M^D = Z_M^H \ (2 - 1\ D)\ D \tag{5.1}$$

for light-demanding species

$$Z_M^D = Z_M^H \ (1{,}7 - 0{,}7\ D)\ D, \tag{5.2}$$

where Z_M^D, Z_M^H — current increment of valuated and regular-density stands correspondingly;

D – stand density.

Extensive studies on how the density affects current increment have been carried out by V.V. Antanaitis and his followers [43, 44]. However, the above mentioned researchers have not derived any special formulas for pine stands of Belarus. Therefore, Gerhard formula is considered to be the most appropriate for light-demanding species.

Thus, basic data for the calculations of carbon sequestration in annual increment of pine stands by age classes are average age across age classes, average growth classes of pine stands across age classes, average density across age classes and current increment of the stands calculated by Gerhard formula.

The optimal age classification is a normal forest theory as specified in the forest inventory reference sources [43, 45, 49, 51, 66, 67, 97]. Nowadays felling age of commercial pine stands correspond to age class 5 (81–100 years). Other forest categories have the felling age that was previously determined for the forests of group 1 (101–120 years). This age is a basic point for determining the optimal age structure in accordance with the normal forest theory.

The maturity age by maximum carbon sequestration (felling age has not been prescribed yet) correspond the ecological maturity of forests.

Other methodological aspects of the present study result from other methodological aspects result from the present study and are described in the relevant chapter of this report, e.g., ecological maturity of forests.

Experimental material for this study is represented by the data taken from the Forest Cadastre as of 01.01.2017 [130], updated information from the databank "Forest Fund" provided by RUE "Belgosles" as well as available reference data on wood moisture and specific weight [118].

This information is given in Tables 22–24.

Review of Table 22 proves that the most represented pine stands are those of 41–60 years of age. Ripening stands have almost accessed optimal rate. At the same time young forests, particularly of age class 1 are lacking. Mature stands have increased as much as almost five times over the past 20 years, however, they have not accessed the optimal volume yet.

Table 22 shows that pine stands volumes correspond to their areas in terms of their age dynamics. Simultaneously, due to decreasing density of mature and ripening stands, their volumes are reduced respectively as compared to normal stands.

Table 22

Distribution of areas and volumes of Belarusian pine stands by areas and age classes as of 01.11.2017

	Age classes											Total
	1	2	3	4	5	6	7	8	9	10	>10	
Area, thousand ha	371.7	374.1	1045.6	1325.9	578.8	99.9	20.6	7.4	6.1	4.7	3.4	3838.2
Volume, thousand m^3	11994.6	46878.6	251307.6	374051.4	163926.6	26578.6	4772.9	1877.6	1822.4	1469.2	1086	885765.5

Distribution of areas and volumes of pine stands is illustrated by Figures 9 and 10.

It should be noted that certain decrease in areas and volumes of pine stands occurred over 10 months of 2017. This was caused by extensive sanitary fellings of pine stands due to their mass drying after being attacked by bark beetle.

From the course "Wood Science" [118] we know that raw-growing (freshly-cut) wood has moisture content of 80–100% depending on growth conditions. Under medium conditions of pine forest growth (mossy pine forest), the moisture content of growing wood ranges from 95% to 100%. Therefore, to make the calculations the specific weight of pinewood is taken at this moisture content value from Table 23.

Table 23

Weight (kg) of solid cubic metre of wood in terms of moisture content

Tree species	Moisture content, %													
	10	15	20	25	30	40	50	60	70	80	90	100	110	120
Pine	500	510	520	540	550	590	640	680	720	760	810	850	890	930

Table 24

Average values of growth classes and density by age classes

Age class	Growth class	Density
1	1.7	0.72
2	1.9	0.76
3	1.4	0.77
4	1.4	0.72
5	2.0	0.69
6	2.6	0.66
7	3.1	0.65
8	2.8	0.65
9	2.1	0.66
10 and over	1.5	0.67

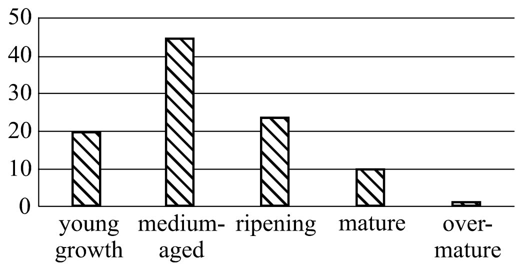

Figure 9. **Distribution of areas of pine stands by age groups, %**

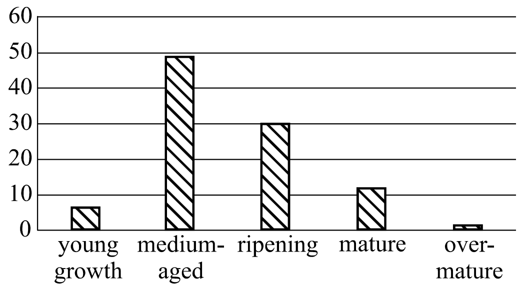

Figure 10. **Distribution of volumes of pine stands by age groups**

Review of Figure 9 and 10 demonstrates that the volume share of medium-age, ripening and mature stands is higher than respective areas of these age groups which is related to increasing stock per 1 ha during forest growth.

5.2. Reserves and increment of sequestered carbon by pine stands across age classes

It has been proved above that climate change is directly related to the rates of carbon dioxide sequestration in which forest plays a crucial part. Extensive research is being carried out on carbon sequestration by forest stands in different countries. Well-known works include those by V.A. Usoltsev [116,117], A.I. Utkin [7], N.A. Moiseev [88], A.S. Isaev [73] and other authors who do studies of the forests of Russia, Western Europe, etc. A vast number of works on carbon sequestration have been published in national and world literature. Over the CIS area, Russian experts have produced the greatest number of works on this issue and created dedicated schools of thought.

In Belarus similar research has been done by the Institute of Experimental Botany of Belarus NAS [69, 70, 75], BSTU [107, 108] and the Institute of Forest of Belarus NAS [92]. The data obtained may differ due to the methodology of study chosen and varying wood stock volume in the forest fund in the course of time. Carbon sequestration by dead wood, forest floor, soils and swamps has been studied by L.N. Rozhkov [108], A.N. Nikitin [92], S.A. Zhdanovich [69, 70], etc. Data about carbon stock and emission have not been comprehensively presented in international publications. Occasionally they were described by foreign authors using Belarusian materials [7]. Therefore, research into more detailed estimation of carbon sequestration volumes is still of immediate interest.

To eliminate or mitigate negative climate change effects in Belarus, substantive actions have been taken to adapt national economy to changing conditions. The most significant of the actions is the Presidential Decree of the Republic of Belarus No. 370 dated 13.08.2005 "On Adopting the Kyoto Protocol and United Framework Convention on Climate Change" and the Resolution of the Council of Ministers of the Republic of Belarus No. 1582 dated 30.12.2005 "On

Implementation of Provisions of the Kyoto Protocol and United Framework Convention on Climate Change for 2005-2012" [99, 101].

The adoption of the above mentioned documents resulted in a number of enactments on greenhouse gases record. Appropriate regulations and actions have been developed by nearly all governmental agencies, i.e., the Ministry of Natural Resources and Environmental Protection, the Ministry of Agriculture, etc. The key aspect here is the adjustment of gross domestic product (GDP) growth rate to the consumption rate of fuel and energy resources (FER) and greenhouse gases (GG) emissions. The GDP growth rate has to considerably exceed the FER consumption rate and GG emissions. The Ministry of Forestry of the Republic of Belarus implements all the actions listed above.

Carbon sequestration is directly dependent on biomass growth and its decomposition rate. In this context it is essential to develop a balance of fellings, reforestation and growing of large-sized timber and conservation of old-growth forests [52, 55, 88, 89, 106, 109, 110, 120].

In the course of studies of carbon sequestration the carbon accumulated by stemwood is of utmost importance. Carbon is fixed by stemwood for a long time, i.e. service life of items made of the wood. Other stand components are disposed relatively fast. So, firewood and most logging residues are burnt with concurrent CO2 emissions into the atmosphere. Therefore, stemwood and merchantable timber are of immediate interest in terms of carbon sequestration. This study takes this factor into account.

Consequently, calculation of the carbon amount fixed by a stand can be made in terms of wood volumes and wood specific weight. The conversion factor for the calculation of carbon amount depends on the forest stand age and tree species. According to different various sources this factor can range from 0.4 to 0.55. Most authors take an average factor of 0.5 to make calculations [54, 57, 6, 105, 106, 115, 117]. This can be justified by the fact that rounding of results is inevitable when using materials of forest fund inventory to make the calculations. Thus, the conversion factor value will not lead to significant errors in the final result.

In a growing stand the specific weight of wood depends on the tree species, age and forest type to some extent. Conversion factors are also indicated in the official methodology for calculation of fixed carbon [6].

When analyzing carbon sequestration by forest stands, mature and overmature stands are the most valuable material for the studies. For stands of older age the conversion factors, i.e. factors of converting volume into weight, are somewhat higher than those for younger stands. This can be attributed to higher density of older-age wood.

Nowadays the information about volume and rate of carbon sequestration is taking on new significance. Sequestered carbon has been commonly used as a decisive factor in regulating the atmosphere and climate. Moreover, it has become essential for the regulation of economic activity. Thus, ecological and ecological-economic forest maturity categories [50,79] have been defined in the Republic of Belarus in order to determine felling ages. Ecological maturity is based upon high correlation dependence (0.85–0.97) between the CO_2 sequestration and other ecological values of forest such as water protection, soil protection, sanitary functions [118]. This fact places even higher requirements to the accuracy of determination of the level of carbon sequestration by our forests.

Forest fund lands occupy 9.56 million ha or 45.4% of the whole territory of Belarus. Forest-covered lands are located on the area of 8.26 million ha, i.e. 39.8% of the total area of the country. The forests are unevenly distributed throughout the country's territory. On most forested lands the share of forests exceeds 60% (Rossonskiy and Lelchitskiy districts) whereas some districts (Nesvizhskiy, Skidelskiy) have only 14–15% [44]. One of the most forested regions is the eastern part of Belarusian Polesye [130].

Our previous studies [48, 51, 141] prove that the growth dynamics of Belarusian forest stands is almost the same across different forest subzones, in other words, our country is basically a uniform forest taxation region.

Contrary to spruce, hornbeam or oak, pine has no expressed preference of forest subzones [51, 82, 112, 113]. In Belarus the share of pine has been ranging from 50 to 60% for over 200 years until now [60, 61, 82, 112, 113, 137].

Pine stands of Belarus have unified felling age which is equal to age class V for forests of group 2 and age class VI for forests of group I [51, 66]. Dedicated studies [49, 51, 66, 68] have proved that for forests of group 2 the felling age is underestimated. It does not meet up-to-date wood consumption trends [66, 68] and criteria of ecological-economic maturity [49, 50].

Studies of pine stands have been carried out for more than 150 years. First research into the growth course done in the mid-XIX century [48, 67, 141] was highly remarkable as well as yield tables by

A.V. Tyurin created in early XX century [115, 116]. Besides stand development issues, the studies also touched upon variability of main taxation parameters in terms of age and growth classes, the effects of the origin, density and geographical location upon the growth of pine stands [43, 44, 45, 47, 48, 51, 66, 72, 77, 82, 83, 89, 109, 112, 113, 120, 122, 115], etc.

Great results have already been achieved in studying pine stands, however, over the recent decades new trends have appeared in the field of studying forests, including pine forests. New approaches are being used now such as mathematical modelling and system analysis. Increased anthropogenic impacts and climate changes are being given consideration too [43, 46, 51, 52, 65, 73, 76, 77, 83, 95, 119, 120].

Economic load upon forests is most apparent in the dynamics, productivity and commodity pattern of model forests. So, the information about their growth and development characteristics forms scientific basis for the evaluation of forest productivity and predictions about forest utilization. Forest fund inventory gives data for such stands.

Growth course and commodity pattern of pine stands in Belarus have been studied by different experts [47, 48, 51, 66, 68, 77, 82, 89, 96, 98, 116, 122]. Their data reveal certain variability, so we use officially approved yield tables [96] to evaluate current increment.

As has been mentioned before, the amount of fixed carbon is calculated by the methodology approved by the Ministry of Forestry and the Ministry of Natural Resources and Environmental Protection [95]. The methodology uses wood stock and increment values and conversion factors to transform wood stock values into available carbon dioxide. These conversion factors average 0.5. Similar methods have been used by domestic and international experts to calculate carbon stock in the forests of Belarus [44, 47, 105, 106, 115, 116, 117]. The total amount of carbon stock was previously estimated at 498.7 million t [105] that is 62 t/ha when transferred into per-one-hectare value of forested lands (8046 thousand ha).

Thus, the review shows that main methods applied to carbon sequestration by pine stands have been well-proven and are recommended to be used for the mentioned purposes.

The determination of ecological maturity is described below.

Carbon stock has been calculated by the methodology described in chapter 2b1. The calculations are given in Table 25.

Table 25

Calculation of total carbon stock in pine stands across age classes as of 01.11.2017

Age class	Stemwood volume, thousand m^3	Specific weight of 1 m^3 of absolutely dry wood	Weight of absolutely dry wood, thousand t	Conversion factor	Carbon stock, thousand t	Current carbon stock change, thousand t/year
1	11994.6	0.510	6117.2	0.480	2936.2	146.8
2	46878.6	0.515	24142.5	0.490	11829.8	444.7
3	251307.6	0.520	130679.9	0.500	65330.0	2675.0
4	374051.4	0.520	194506.7	0.500	97253.3	1596.2
5	163926.6	0.521	85405.8	0.505	43129.9	–2706.2
6	26578.6	0.522	13874.0	0.505	7007.4	–1806.1
7	4772.9	0.530	2529.6	0.515	1303.7	–285.2
8	1877.6	0.540	1013.9	0.515	522.1	–39.1
9	1822.4	0.540	984.1	0.515	506.8	–0.8
10	1469.2	0.540	793.4	0.515	408.6	–4.9
10 and onward	1086	0.541	587.5	0.516	303.1	–5.3
total	885765.5	–	460634.6	–	230530.9	15.1

The review of Table 25 illustrates that pine stands of Belarus have accumulated 230.5 million t of carbon. The greatest accumulation can be observed in age class 3 (65.3 million t) and age class 5 (43.1 million t). Young forests have minor average carbon stock per 1 ha and occupy relatively small areas, so they accumulate less carbon, i.e., age class 1 – 2.9 million t, age class 2 – 11.8 million t. From age class 6 and onwards the carbon accumulation sharply declines due to the small amount of pine stands of these ages. As old-aged pine stands occupy smaller areas, average carbon stock values of growing stands start to decrease in age class 5 and onward age classes. On average current changes in carbon stock remain relatively steady (15 thousand t). Increased calculated felling rates will result in further decrease in old-growth forests and annual carbon sequestration in stemwood.

Carbon stock in pine stands across age groups (%) are shown in Figure 11.

Figure 11 illustrates that the largest carbon amount is accumulated by medium-aged and ripening stands (almost 80%). Young forests have inconsiderable carbon accumulation (6%) due to their small stemwood volume.

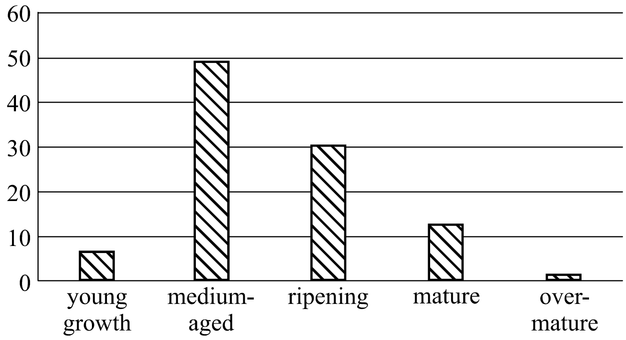

Figure 11. **Carbon stock in pine stands across age groups, %**

Average stock change shows stock change in growing forest but not the amount of loss. It is widely known that current wood increment is estimated not by the amount of the available stock but by general productivity of trees [45, 115]. Current increment of stands is calculated by general productivity of trees by means of the following formula:

$$Z_M^{cur} = M_A - M_{A-n} + O_n \qquad (5.3)$$

where Z_M^{cur} – current increment in stock at age A;

M_A – stock at age A;

M_{A-n} – stock at age $A-n$;

O_n – amount of loss over n years.

In a factual pine stand the current increment depends on density and is calculated by means of Gerhard formula.

$$Z_M^D = Z_M^H \ (1{,}7 - 0{,}7\ D)\ D, \qquad (5.4)$$

where Z_M^D, Z_M^H – current increment in evaluated and normal stands respectively;

D – stand density.

Having data about current increment at density 1.0 and information about average growth classes and average density of pine stands across age classes provided to us by RUE “Belgosles”, we were able to estimate current increment of Belarusian pine forests across age classes. Values of current increment at density 1.0 were taken from Belarusian yield tables. As the tables show data only for forests aged 140 and under, current increment values for age class 8 and onwards were established by extrapolation method.

Calculated current increments across age classes in terms of growth class are given in Table 26. .

Table 26

Current increment of pine stands of Belarus across age classes

Age class	Growth class	Density	Current increment at density 1.0, m^3/ha	Current increment at modal density, m^3/ha
1	1.7	0.72	3.4	3.4
2	1.9	0.76	10.6	9.1
3	1.4	0.77	11.6	10.4
4	1.4	0.72	10.2	8.8
5	2.0	0.69	7.7	6.5
6	2.6	0.66	5.5	4.5
7	3.1	0.65	4.0	3.2
8	2.8	0.65	3.5	2.8
9	2.1	0.66	3.0	2.4
10	1.5	0.60	2.5	1.9
10 and onward	1.3	0.50	2.0	1.35

Table 26 shows regular variations of current increment with advancing age that correspond to the formerly established regularities of forest taxation [44, 45, 51, 100].

Current carbon increment across age classes is given in Table 27 and Figure 12. To facilitate the calculations, factor K_3 was introduced. $K_3=K_1*K_2$, where K_1 – weight of 1 m^3 of absolutely dry pinewood by age classes, K_2 – conversion factor by age classes.

Data of Tables 25 and 27 and Figure 12 show that annually about 15 thousand t of carbon is added to stemwood of growing stands of the up-to-date age structure. This proves the fact that the amount of carbon in stemwood of growing stands remains relatively stable. Current carbon increment in pine stands (including loss) is 8180 thousand t. This means that approximately 8000 thousand t of carbon is accumulated in dead wood, i.e. about 4% of the carbon fixed by stemwood.

The above values of the total carbon amount accumulated by pine stands, its average annual changes and current carbon increment across age classes are based upon the data of 01.11.2017 (in fact of 01.01.2018) that have been provided to us by RUE “Belgosles”. The present task requires to make predictions about carbon accumulation in pine stands across age classes and its current changes until 01.01.2031.

Table 27

Current carbon increment by age classes

Age class	Area across age classes, thousand ha	Current increment per 1 ha, m^3 per annum	Total current increment across age classes, thousand m^3	Factor K_3	Total current carbon increment, thousand t per annum
1	371.7	3.4	1263.8	0.245	309.6
2	374.1	9.1	3404.1	0.252	857.8
3	1045.6	10.4	10874.2	0.260	2827.3
4	1325.9	8.8	11667.9	0.261	3045.3
5	578.8	6.5	3762.2	0.263	989.5
6	99.9	4.5	449.6	0.264	118.7
7	20.6	3.2	65.9	0.273	18
8	7.4	2.8	20.7	0.278	5.8
9	6.1	2.4	14.6	0.278	4.1
10	4.7	1.9	8.9	0.278	2.5
10 and onward	3.4	1.3	4.6	0.279	1.3
Total	3838.2	–	31536.5	–	8179.9

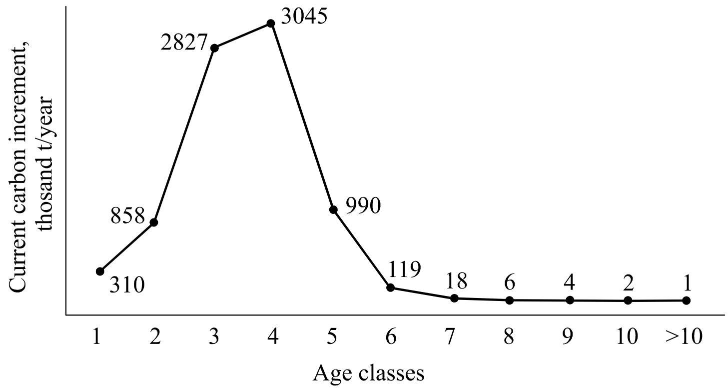

Figure 12. **Current carbon increment by age classes**

The calculations have been made in terms of changing areas of pine stands by age classes for the subsequent 13 years, i.e., from 2018 to 2030. The prediction about the area changes until 01.01.2031 has been made by means of the method commonly applied in forest inventory. Average wood stock per 1 ha across age classes has been set to the current value. The calculation of the amount and current change in carbon increment across age classes is given in Table 28.

Table 28

Carbon stock in stands and its current changes across age classes as of 01.01.2031

Age class	Areas by age classes, thousand ha	Average stock, m^3/ha	Wood stock by age classes, million m^3	Factor K_3	Carbon stock by age classes, thousand t	Average annual change in carbon stock by age classes, thousand t/year
1	519.2	32.3	16770.2	0.245	4108.7	205.4
2	372.3	125.3	46649.2	0.252	11755.6	382.3
3	608.2	240.3	146150.5	0.260	37999.1	1312.2
4	1140.2	282.1	321650.4	0.261	83950.8	2297.6
5	969.0	283.2	274420.8	0.263	72172.7	–588.9
6	188.1	266.0	50034.6	0.264	13209.1	–2948.2
7	7.2	231.7	1668.2	0.273	455.4	–637.7
8	16.0	253.7	4059.2	0.278	1128.5	33.7
9	6.9	298.8	2061.7	0.278	573.2	–27.8
10	5.6	312.6	1750.6	0.278	486.7	–4.3
10 and onward	5.5	278.5	1531.8	0.279	427.4	–3.0
Total	3838.2	–	866747.1	–	226267.1	21.4

Tables 25 and 28 show that by 2031 the carbon stock in pine stands will have remained almost the same. Decrease in total carbon stock is inconsiderable making up only 2%. This can be explained by the fact that main carbon sinks are age classes 3, 4 and 5 that occupy sufficiently large areas. Moreover, annual cuts are not to be considerably increased by 2031.

Average annual change in carbon stock per 1 ha by age classes also reveals small changes: from 15.4 thousand t to 21.4 thousand t. After 2031 the changes in carbon stock will be more substantial due to increased annual cuts and decreased stock of age classes 3 and 4.

The review shows that main carbon accumulation occurs in age classes 3 and 4. If annual cuts are to be decreased, the carbon discharge through the wood harvest will exceed its accumulation by standing trees.

The increase of carbon stock in pine stands is determined by increasing wood volumes. It is common knowledge that wood stock of a certain tree species throughout the country depends on the area and average wood stock across age classes. The average wood stock is directly dependent upon the annual increment.

5.3. Optimization of age structure of stands based on ecological maturity of forest

Age structure of stands is a determining factor for the calculations of allowable cut. That's why this issue is widely addressed in reference sources [43, 49, 50, 51, 66, 67, 80, 89, 97].

Forest inventory considers the age structure to be optimal when it is in line with the theory of normal forest [51, 67, 107]. The estimation of age groups is based on the established felling ages. The latter are calculated by forest maturity types that have varied over time. The forest maturity is one of the most important concepts of forestry. It has been studied by many prominent researchers – silviculturists, forest inventory experts and forest economists [43, 49, 50, 51, 57, 67, 68, 77, 78, 79, 80, 86, 97, 114].

Their works delve into the essence of maturity, provide its classification, define maturity ages for main forest-forming species of Europe, North America and other continents, give insight into the dependency of forest maturity upon allowable cuts. They tackle a number of other particular issues, i.e., dependence of forest maturity on growth conditions and forest type, model of average increment maximum, etc.

At the same time many aspects of forest maturity have not been given thorough consideration. First of all, economic and ecological aspects of forest maturity have been underanalyzed due to the ever-changing conditions of economy. The ecological aspect of forest maturity has been given attention only in recent decades as a result of the emerging environmental concerns all over the world.

Forest maturity is defined in almost all forest inventory textbooks and many research papers [43, 49, 50, 51, 67, 80, 89, 99, 124, etc.]. The versions are generally consistent and reveal only minor variations. Forest maturity is defined as a state of a forest stand when it reaches certain age and is optimally exploitable for some economic or ecological purposes.

Another definition of forest maturity that is worth mentioning was made by M.M. Orlov, the father of forest inventory and forest economy [97]: "Forest maturity is a state of forest stands and trees determined by the age when they are most appropriate for the intended uses". Although M.M. Orlov did not consider the ecological values of forest (they were hardly recognized 90-100 years ago), his definition is comprehensive enough to be applicable nowadays.

A great number of forest maturity types are distinguished based on the multiple functions of forests, i.e., natural, regenerative, quantitative, technical, economic, financial, etc. [43, 49, 50, 51, 68]. Before the Revolution and until the 1930s economic, qualitative and financial forest maturity was of great importance. In the Soviet times and until today the felling age of commercial forests is determined by quantitative and technical maturity [51, 68, 92]. Due to the increased importance of ecological values of forests the forest maturity of ecological character has got widespread, i.e., water protection, soil protection, recreational, etc.

Today the forest inventory distinguishes quantitative, technical, natural, regenerative, financial, economic and other types of forest maturity [51, 68]. Not dwelling upon each type mentioned, it should be noted that in our country felling age is established based on technical maturity. This maturity corresponds to the age when average increment of one or a group of principal wood assortments reaches its maximum value.

As described in the studies by K.E. Nikitin [93, 94], the maximum value of average increment is reached at the crossing of graphs of the current and average increment.

Felling age has been determined by technical maturity for more than 90 years. Nowadays this parameter alone is not sufficient. Therefore new forest maturity types have been derived, i.e., economic and ecological ones: water protection, soil protection, etc. [43, 49, 50, 51, 68, 80, 114].

At the same time, until recently the calculations of forest maturity types have not taken into account one of the parameters that is the most essential to forest utilities – carbon sequestration. Therefore, ecological maturity as a special maturity type has been developed.

The diversity of ecological functions of forest results in multiple categories of forest group I. In the former USSR they amounted to 25 categories. In Belarus their number is lower due to minor variability of climatic and geographical conditions [51, 68, 81].

The diversity of forest categories causes many maturity types of ecological character: water protection, sanitary, protective, etc. The information about the ages of ecological maturity (often referred to as special) is rather controversial. So, B.A. Kozlovskiy [115] believes that water protection maturity corresponds to the age of technical maturity whereas protective and sanitary-hygienic are one age class onward. At the same time, fundamental studies by F.P. Moiseenko and

N.K. Bobkov [116] consider that water protection maturity of pine stands in Belarus corresponds to the age of 110–120 years.

Modern opinions of ecological maturity define it as the maximum age beyond which the stand begins losing its ecological values, so different forest categories reach their ecological maturity at old ages on the verge of natural maturity.

The diversity of maturity types of ecological character makes it difficult to apply a generalized environmental approach to forest utilization in the forests belonging to ecological maturity type. The diverse criteria make it impossible to set aside a principal ecological component when determining the maturity age as a constructing element of ecologically sound forest management system.

As pointed out by A.V. Neverov [91] the integrated process of natural resources reproduction is split by material production and environmental sphere. He also notes that economic aspects of the reproduction should be studied in terms of ecological aspects. Therefore it is essential to create an ecological-economic system which is an integration of economic relations in the forest sector and impacts of nature (environmental) factors. Only by creating a system and applying a system approach towards the issues of ecological-economic regulation (as noted by O.S. Shimova [126]), scientific-theoretical basis for economic mechanism of nature management can be defined.

This system includes forest maturity as one of the main constructing components of ecologically sound forest management. It specifies not only the time necessary for the reproduction of forest resources but also the volume of differently-aged stands that ensure ongoing forest management over a certain area. Only in this case forest as a stabilizer of environmental conditions can be reviewed in terms of geographical location, forest cover of the area, economic nature of labour forces and correspondence of spatial and age structure of forests to the vital services of the country and the region [91, 100, 111]. Therefore it is recommended to use one universal maturity criterion instead of multiple ones.

This criterion should serve to calculate ecological-economic effects when doing various ecological-economic evaluation of nature protection and nature management activities with regard to spatial and time factors.

In the conditions of Belarus it is necessary to use forest stands for multiple purposes by combining the different functions of single-purpose forests. All stands have water protection and protective functions, are a source of wood and other resources, serve as recreational sites [50, 51, 68, 79, 100]. When identifying a universal parameter of ecological maturity and analyzing the current environmental conditions we can establish that protective, water protection and sanitary-hygienic functions of forest are restricted to a local level ranging from a small district to relatively large region. Recreational forests are intended to provide necessary sanitary-hygienic conditions around one or several health resorts or holiday centres. Usually their area is limited to 2–3 thousand ha. Water protective forests influence the conditions of water sources within a catchment basin covering larger or smaller region. Their influence area is spread to hundreds and thousands of square kilometers depending on the catchment basin and forested land areas.

The most significant global role of forests is their ability to deposit carbon dioxide and to produce atmospheric oxygen. It is the ecological function that is defined as the primary one by all leading experts in this field [42, 50, 51, 52, 55, 60, 73, 75, 77, 88, 99, 101, 105, 107, 108, 114]. Most experts place great emphasis on CO_2 sequestration. It is noted that the mankind will not suffer from the shortage of oxygen in the foreseeable future; however, the oxygen release is tightly bound to carbon dioxide absorption. The carbon dioxide yet causes temperature changes on the planet. The increase in CO_2 content in the atmosphere has amounted to 25% over the past 50 years [101]. This process is of progressive nature and is of great concern all over the globe [100, 101, 109, 114].

The above experts note that CO_2 can be excluded from the atmosphere only by photosynthesis. Forests play a decisive role here. Most amount of carbon dioxide is absorbed by rainforests. However these regions are also the fastest to release carbon dioxide back into the atmosphere. Boreal and nemoral forest ecosystems have slower carbon sequestration rates but are able to retain carbon over long periods of time which makes them as significant as rainforests [114, 7, 116]. Young and medium aged forests fix carbon dioxide at faster rates, but it is old-aged forests that retain carbon over long periods.

Thus, the uppermost ecological function of forests is CO_2 sequestration. Maximum effect can be achieved through a normal forest model with an intensive cutting cycle.

Determination of a universal parameter of ecological maturity in terms of CO_2 sequestration is expedient also due to the fact that it can be based upon wood stock and increment values. These taxation parameters are closely related to other ecological utilities of forest.

Today attempts have been made to develop factors of ecological efficiency of forests that could integrally express their ecological utility [118]. In this case relative factors of each utility can be derived from a multiple combination of utilities. Each factor is a percentage of some limiting values of reference utilities. The factors depend on tree species, growth locations, density, age and other parameters. Correlation analysis of the values cited by the authors of the new approach (Table 29) has shown that CO_2 sequestration is a determinant factor. Very high and reliable correlation factors are found due to the relation of the above factor to O_2 emission, release of biologically active substances (sanitary-hygienic functions), dust retention (antierosion function), to wood stock and increment as well as to the ecological efficiency factor (Table 29). Somewhat smaller correlation is observed in terms of the release of biologically active substances as this is closely related to tree species.

Table 29

Correlation between the amount of the sequestered carbon dioxide and other ecological functions (by basic data of M.A. Kutsevalov, V.V. Uspenskiy, A.K. Artyukhovskiy) [128]

Function	Correlation factors for arguments					
	CO_2	O_2	BAS	DR	Z_M	F_E
CO_2	1.000	–	–	–	–	–
O_2	0.996	1.000	–	–	–	–
BAS	0.681	0.699	1.000	–	–	–
DR	0.963	0.984	0.701	1.000	–	–
Z_M	0.991	0.981	0.656	0.939	1.000	–
F_E	0.990	0.995	0.748	0.978	0.981	1.000

Legend: CO_2 – carbon dioxide absorption; O_2 – oxygen emission; BAS – release of biologically active substances (sanitary-hygienic function); DR – dust retention, antierosion functions; Z_M – increment, m^3; F_E – ecological efficiency factor of stands by the classification of the authors above.

From mathematical statistics it is known that if argument factors are highly correlated between each other, they are to be excluded from the multiregression equation. In this case one leading argument is present in the equation [46, 56, 58, 64, 71, 85]. Therefore we rightfully establish a quantitative relation of ecological utilities of forest to one integral parameter, i.e., carbon sequestration. This factor is a basic one for the determination of ecological maturity of forest.

Thus, if age of ecological maturity is based on the carbon sequestration factor, we "hide" almost all other ecological utilities of forest. The remaining issue to consider is to give the right definition of ecological maturity. It is required that its value reflects all other utilities to the fullest extent which proves to be possible at considerably old age. It should be taken into account that according to forest inventory practices the ages of special ecological maturity range from 90–100 to 140–160 years for coniferous stands.

Thus, the ecological maturity of forest is a state of stands at the age when it has maximum ecological efficiency of ongoing forest management. It is characterized by maximum average annual productivity expressed as maximum average increment. This parameter includes the process of forest reproduction making conditions for ongoing forest management in terms of "space-time" aspect. Special emphasis should be placed on the "space-time" aspect. If we consider forests in a discrete state, i.e., we break the links between time and location, we can evaluate only an individual forest stand. In this case the maximum average increment results in quantitative maturity [43, 50, 61, 68, 86]. To cater for resource and ecological needs in forest products, the whole forest fund territory must be considered in terms of space-time relationships. Therefore, the maximum average increment values should be calculated not for an individual stand but for the whole collection of stands within a working circle.

Hence is the question of the minimum value of this collection as the maximum forest area to be analyzed can cover a whole country or the globe. Studies by N.A. Moiseev [87], N.A. Moiseev and V.S. Tchuenkov [86] claim that a forestry enterprise should be taken as a primary unit of record. In the conditions of Belarus and European part of Russia this unit covers a forested area ranging from 50 to 150–200 thousand ha. A forestry enterprise in Belarus averagely occupies an area of 100 ha [61].

It is known that a starting point in distributing stands by age classes is the established felling age [51, 68]. The change of maturity and felling ages will lead to a new distribution by age classes and changing areas of age groups. Less intensive cutting cycles result in increasing cut areas as compared to more intensive ones. This causes changes in average increment on a territory that is nearly equal to a large forestry enterprise.

The age of ecological maturity has been calculated by simulation modelling of average increment changes in a collection of stands.

Average increment values have been calculated for various age structures allowing for the presence of normal forest. It is the model that illustrates average increment changes in a collection of stands with various cutting cycles. Table 30 and Figure 13 show average increment values for all stands of growth class II within a working circle for various felling ages.

Table 30

Average increment per 1 ha within a working circle, pine stands of growth class II, various felling ages

Felling age, years	Average increment within a working circle, m^3/ha	
	normal stands	Modal stands
60	4.18	3.19
80	4.39	3.20
100	4.62	3.28
120	4.64	3.28
140	4.59	3.08
160	4.48	2.93

Table 30 and Figure 13 allow us to conclude that the largest average increment within a pine working circle is observed at the age ranging from 100 to 120 years. Consequently, the largest sum-total wood stock occurs at the same age. The same can be concluded about the largest amount of carbon sequestration by the pine forests under study.

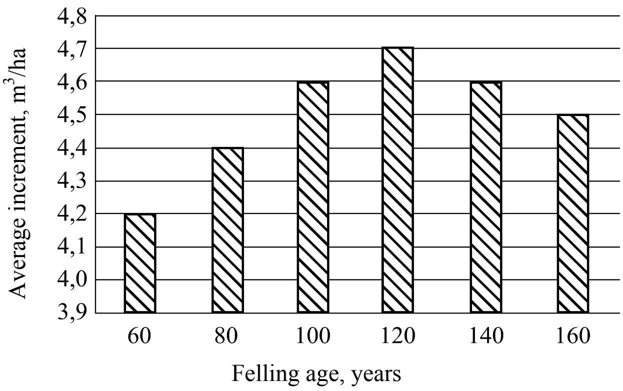

Figure 13. **Average increment per 1 m^3/ha of a collection of pine stands of growth class II at various felling ages for normal stands**

Similar calculations by means of simulation modelling for all growth classes made it possible to estimate ecological maturity of pine stands. The calculations are very extensive and have been published by various sources before [78, 79, 80], so they are not included in the report. The calculated ecological maturity ages are given in Table 31.

Table 31

Ecological maturity ages of Belarusian stands

Ecological maturity age (years) by growth classes					
Normal stands					
I[a]	I	II	III	IV	V
105	110	115	120	130	140

Table 31 illustrates that ecological maturity is reached at a considerably older age than quantitative maturity. This can be explained by the fact that space-time structure changes. When cutting cycles are established at 60–80 years, a large share is taken by young forests of age class I that is characterized by low volumes. Cutting cycles of 140–160 years lead to the predominance of stands with slow increment. Thus, the largest average increment in the stand collection can be observed at the age ranging from 100 to 140 years, i.e., a territory with the optimal combination of stands of age classes I, II, III, IV, V and VI.

Analysis of ecological maturity shows that its age is approximately one age class higher than felling age of commercial forests and matches the felling age of ecological forests. Exclusive of swampy pine stands of growth classes IV and V, ecological maturity can be estimated as age class IV that embraces ecological maturity ages for growth classes I[a] to III. Age class IV can serve as a basis for the calculation of the optimal age structure of stands by means of maximum carbon dioxide sequestration.

Age structure of pine stands in Belarus is far from being perfect. Unsustainable cuts of pre-war, war and post-war periods caused sharp reductions of mature stands. Low allowable cuts over the past 40 years have led to considerable decrease in young forests. Table 32 shows the present-day age structure of pine forests by the data of Forest Cadastre as of 01.01.2017 [130].

As can be seen from the Table, medium-aged stands are predominant ones whereas young forest and mature stands are lacking.

Table 32

Area and stock of pine stands by age groups (%)

Age group	Area	Stock
Young forests	18.4	6.4
Medium-aged	42.7	47.2
Ripening	28.0	33.8
Mature and overmature	10.9	12.6
Total	100	100

Based on the theory of normal forest, the optimal age structure for current felling ages is given in Table 33.

Table 33

Optimal distribution of forests by age classes in the Republic of Belarus (percentage of the area taken by the tree species) for current felling ages

Tree species	Felling age	Age classes									Total
		1	2	3	4	5	6	7	8	9	
Categories of ecological forests											
C	101	18	17	17	16	16	16	–	–	–	100
Commercial forests											
C	81	22	21	20	19	18	–	–	–	–	100

Table 33 shows that at the established current felling ages, commercial forest should contain 43% of young forests, 20% of medium aged, 19% of ripening and 18% of mature ones.

The category of ecological forests where felling ages are set to 101–120 years medium-aged forests comprise age classes 3–4. Thus, the optimal stand percentage by age groups looks as follows: young forests – 35%, medium-aged – 33%, ripening – 16% and mature – 16%.

The optimal stand distribution by age classes is slightly imbalanced towards young forests. During forest growth a certain share of young or medium-aged forests are inevitable cleared as a result of forestry-related catastrophic events or other effects. So, according to the theory of normal forest it is necessary to have sufficient amount of mature forests suitable for cutting.

As has been mentioned before, ecological maturity of pine stands of growth classes I^a –III corresponds to age class 6. The optimal age structure of pine forests calculated by optimal carbon sequestration matches the nature protection categories of Table 31.

Stands of low growth classes have higher ecological maturity and different age structure: class 1 – 17%, 2 – 16 %, 3 – 15%, 4 – 14 %, 5 – 13 %, 6 – 13 %, 7 – 12 %.

This being the case, medium-aged stands embrace age classes 3, 4 and 5. The distribution of age groups looks as follows: young forests – 33%, medium-aged – 42%, ripening – 13% and mature – 12%. Stands of low growth classes accumulate substantially lower carbon amount and are of low economic significance, so the uniform optimal age structure of pine forests should be based on the principle of maximum carbon sequestration over the whole life of a stand, i.e., young forests – 35% (age class 1 – 18%, 2 – 17%), medium-aged – 33% (age class 3 – 17%, 4 – 16%), ripening – 16% (age class 5 – 16%), mature – 16%.

The optimal distribution of pine forests by age groups is shown in Figure 14.

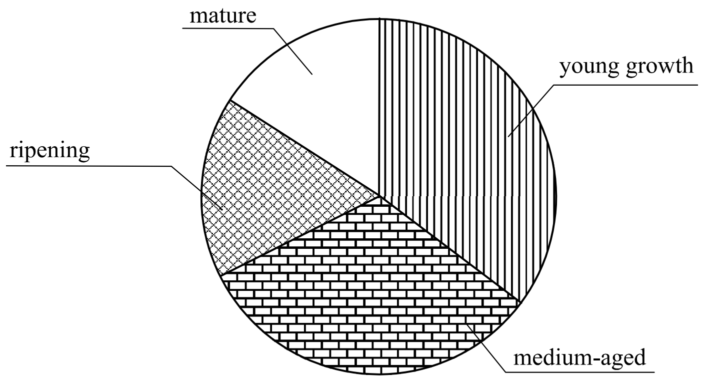

Figure 14. **The optimal distribution of pine forests by age groups, %**

If pine forests of Belarus match the age structure shown in Figure 14, forest management will be carried out in accordance with the theory of normal forest.

The foregoing information allows us to conclude that the optimal carbon accumulation by pine stands is achieved by the age structure when felling age corresponds to that of ecological maturity (age class 6). The share of each age class should be as follows: age class 1 – 18%, 2 – 17 %, 3 – 17 %, 4 – 16 %, 5 – 16 %, age class 6 – 16 %. This age structure can gradually be achieved in 30–40 years, i.e., by 2050–2060. Furthermore, the allowable cut has to be slightly reduced between 2031 and 2050. By this time, the current medium-aged ripening stands will become mature ones, so their clear cutting will result in sharp decrease in forest use which is contradictory to the theory of normal forest. Increasing the felling age by one age class will make it possible to smooth the allowable cut regulation.

The optimal distribution by age groups and classes based on the ecological maturity is considerably different from the current age structure of pine forests.

To achieve the optimal age structure of forests it is necessary to increase the share of young and mature forests. Taking into account the fact that felling ages are strictly prescribed and regulated in Belarus, it represents a tough challenge. Some actions that would improve the age structure of pine forests include:

– increasing the share of young forests;

– regulation of allowable cuts in pine forests in order to reduce it in 2040-2060 to optimize the age structure.

Adapting the felling ages to age class 6 will not lead to considerable decrease in allowable cuts. The fact is that nowadays commercial stands cut at age class 5 must amount to 18% of the total area of all stands within a working circle. According to the new age structure the to-be cut stands of age class 6 make up 16% of the whole working circle. This being the case, the decrease in cut areas must be compensated by additional increment over 20 years. When changing from age class 5 to age class 6, density must remain unchanged as prescribed by the cut regulations in Belarusian forests [103].

All the measures listed above involve considerable expenses and long time of implementation. Thus, the age structure of stands can be optimized not earlier than 2050–2060. The measures must be contained in a special program with appropriate time scheduling and allocation to forestry establishments. This can be done during forest inventory when developing forest inventory plans.

5.4. Conclusions

To sum up the information above we can make the following conclusions.

1. In spite of the availability of extensive and in-depth studies on carbon sequestration by forests and its climate impacts, many issues

have not been given proper attention, e.g., determination of carbon stock and increment in Belarusian forest stands across age classes and opportunities of carbon sequestration. Therefore the present study is of great current interest.

2. Total carbon stock sequestered by pine stands amounts to 230.5 million t. The largest amount is found in age class 3 (65.3 million t), age class 4 (97.2 million t) and age class 5 (43.1 million t). Young forests are characterized by inconsiderable average stock per 1 ha and accumulate far less carbon, i.e., age class 1 – 2.9 million t, age class 2 – 11.8 million t. From age class 6 and onward the carbon sequestration is sharply reduced due to small areas of the pine stands. The decreasing areas of pine stands at older age result in the average reducing carbon accumulation at age class 5 and onward. Current annual change in carbon accumulation remains relatively steady in pine stands (15 thousand t). The increase of allowable cut volumes will lead to the reduction of old-aged pine forests and annual carbon sequestration by stemwood.

3. Annual current carbon increment across age classes includes carbon sequestered by wood debris equaling to 8 million t or 4% of the carbon accumulated by stemwood.

4. As estimated for 01.01.2031, the carbon stock in pine forests will remain virtually unchanged. The decrease of the total carbon amount is very small and makes up only 2%. This can be explained by the fact that main carbon sinks are stands of age classes 3, 4 and 5 that cover large areas and the allowable cut volumes are not to be increased by 2030.

Similar predictions about the average carbon stock changes per 1 ha across age classes claim they will not change considerably as well, i.e., from 15.4 thousand t to 21.4 thousand t. From 2030 and onward the carbon accumulation by pine stands will experience more severe changes due to the increasing allowable cut volumes and decreasing stands of age classes 3 and 4.

5. The present-day age structure of pine forests does not meet the requirements of the theory of normal forest owing to considerable lack of young forests and certain scarcity of mature forests with predominant medium-aged stands. Nevertheless, optimal distribution of stands by age classes in accordance with the theory of normal forest will not ensure maximized carbon accumulation due to the fact that felling ages are established based on the technical maturity of large and

medium-sized commercial timber. Moreover, the felling ages do not allow maximum wood accumulation within a working circle over the whole life period of a stand.

6. Maximum carbon accumulation by pine forests is possible only when the felling age is established based on ecological maturity. The ecological maturity of forest is determined by maximum average carbon increment over the whole life period of a stand within a working circle.

7. Ecological maturity of pine stands corresponds to age class 6, i.e., 101–120 years.

8. Based on the ecological maturity and the theory of normal forest the optimal distribution of stands by age classes looks as follows: age class 1– 18 %, 2 – 17%, 3 – 17 %, 4 – 16 %, 5 – 16 %, age class 6– 16%.

9. The optimal age structure of pine forests can be attained only by 2050–2060.

10. In order to attain the optimal age structure of pine forests, it is necessary to impose certain restrictions on the allowable cut volumes between 2031 and 2050. By this time the present-day medium-aged ripening stands will turn into mature ones, so their clear cutting can dramatically reduce forest uses, which is contradictory to the theory of normal forest.

11. To increase carbon sequestration by pine forests and to optimize their age structure, the following actions can be recommended:

– establishing pine formations on the felling areas of former birch forests. Until 2031we can expect about 500 thousand ha of birch stands to be cut (230 thousand ha of mature stands and nearly 200 thousand ha of ripening stands that are to become mature in 10 years). Pine plantations can be created on about a half of the areas taking up 10-15 thousand ha per annum;

– restoration of low-value birch stands. The total restoration reserve can make up 10–15 thousand ha. Taking into account the fact that this activity proves to be rather costly, the factual restoration area will obviously comprise 3–5 thousand ha;

– establishing pine plantations on non-forested lands. This reserve is not very ample, however it can amount to 3 thousand ha per annum.

This being said, the total increase of pine stands area can be estimated at annual 16–21 thousand ha. Pine forests can be planted on the former felling sites of spruce, aspen and grey alder stands in southern (spruce) and northern (grey alder) regions.

– regulation of allowable cuts in pine forests in order to reduce it in 2040-2060 to optimize the age structure. This being the case, the allowable cuts for age class 6 will remain more or less the same. According to the theory of normal forest, the optimal distribution of stands must involve 18% of mature stands of age class 5 and 16% of age class 6. The minor decrease in mature forests must be compensated by additional increment over 20 years.

12. All the measures listed above involve considerable expenses and long time of implementation. Thus, the age structure of stands can be optimized not earlier than 2050–2060. The measures must be contained in a special program with appropriate time scheduling and allocation to forestry establishments. This can be done during forest inventory when developing forest inventory plans.

13. Forests of Belarus are a major natural renewable economic asset of the country. Belarus has to maximize the forest cuts in order to ensure ongoing supply of timber and wooden products to domestic and external markets. Maximization of carbon sequestration by Belarusian forests can only be achieved through reduced forests uses. Thus, the measures on increasing the carbon sequestration must be accompanied by international compensation (through CO2 quotas) for the economic losses resulting from the reduced timber volumes brought to the markets. Only under these conditions it will be feasible to maximize the carbon sequestration by Belarusian forests.

6

EFFECT OF THE SPECIES STRUCTURE ON THE CARBON DIOXIDE ABSORPTION BY FORESTS

Reference sources [131, 132] envisage optimization of the tree species and age structure of forests. The optimization of the tree species structure is planned by the transition programs for the optimal tree species structure of forests to be implemented by SPFAs and forestry enterprise. This is of crucial importance for sustainable forest management, rational forest use and regeneration [139]. From this perspective it is important to know how the transition to the optimal tree species structure will affect the carbon balance in Belarusian forests.

6.1. Comparative analysis of the level of carbon dioxide absorption of by plantations of various species groups

The total area of the forest fund lands is 9.57 million ha (as of 01.01.2017 [133]), of which forested lands occupy 8.26 million ha or 86.3%. The forests cover 39.8% of the total territory of the Republic of Belarus. The forests contain about 20 tree species with the principal species of pine (50.2% of the forested lands and 55.6% of the wood stock), spruce (9.3% of the forested lands and 11.1% of the wood stock), oak (3.4% of the forested lands and 2.9% of the wood stock), birch (23.1% of the forested lands and 18.6% of the wood stock), black alder (8.6% of the forested lands and 7.8% of the wood stock), aspen (2.2% of the forested lands and 2.1% of the wood stock), other (3.2% of the forested lands and 1.9% of the wood stock). Average age of Belarusian forests is 55 years, average growth class is 1.6.

Shares of main tree species in the forested lands by wood stock have been adopted to make further calculations (Table 34).

Table 34

Carbon content in phytomass of Belarusian forests

Code	Carbon pools	Carbon content as of 01.01.2017, thousand tC/%
Pool 1, Cp	Carbon content in phytomass of pine plantations of the Republic of Belarus	375192.2 54.3
Pool 2, Cs	Carbon content in phytomass of spruce plantations of the Republic of Belarus	69127.4 10.0
Pool 3, Co	Carbon content in phytomass of oak plantations of the Republic of Belarus	30245.1 4.4
Pool 4, Cb	Carbon content in phytomass of birch plantations of the Republic of Belarus	140782.3 20.4
Pool 5, Cbla	Carbon content in phytomass of black alder plantations of the Republic of Belarus	56231.5 8.1
Pool 6, Cas	Carbon content in phytomass of aspen plantations of the Republic of Belarus	11794.7 1.7
Pool 7, Cother	Carbon content in phytomass of aspen plantations of the Republic of Belarus (larch, hornbeam, ash, maple, elm, grey alder, linden, poplar, woody willow, apple, etc.)	7568.6 1.1
Pool 8, Csw	Carbon content in stemwood of forests of the Republic of Belarus	477823.5 69.2
Pool 9, Cbr	Carbon content in branches of forests of the Republic of Belarus	89289.1 12.9
Pool 10, Cnl	Carbon content in needles or leaves of forests of the Republic of Belarus	33247.1 4.8
Pool 11, Cubm	Carbon content in roots (underground biomass) of forest ecosystems of the Republic of Belarus	82999.7 12.0
Pool 12, Cyg.	Carbon content in young growth of forests of the Republic of Belarus	886.2 0.1
Pool, Cflc	Carbon content in live forest cover of forests of the Republic of Belarus	6696.2 1.0
Pool 14, Cphyt	Carbon content in phytomass of forests of the Republic of Belarus	690941.8 100

The calculations of the total carbon sequestration by tree species and stand components [Table 34] have been made by reference source [6] adapted for the conditions of the Republic of Belarus. Table 34 shows that:

– the largest carbon content (54.3%) is registered in pine plantations which is the predominant one in Belarus;

– the main share of carbon (69.2%) is fixed by stemwood;

– total carbon amount in phytomass of Belarusian forests is 690941.8 thousand t or 690.9 million t and has increased by 56.9% as compared to 2009 [135].

6.2. Comparative analysis of the level of carbon dioxide absorption by various species.

The carbon stock in phytomass depends on tree species (Table 35). The carbon content in the phytomass of tree species has been estimated by its accumulation in 1 m^3 of stemwood across stand components and understorey plants [6].

Table 35

Carbon stock in phytomass of different tree species

Tree species	Carbon stock in phytomass, kg/m^3	CO_2 absorption level, t/m^3
Pine	380.5	1.38
Spruce	352.5	1.29
Oak	590.5	2.14
Birch	426.5	1.54
Black alder	408.5	1.49
Aspen	319.5	1.15

The largest carbon sequestration occurs in oak phytomass (590.5 kg/m^3), the smallest in aspen phytomass (319.5 kg/m^3). The highest level of carbon dioxide absorption is observed in oak plantations (2.14 t CO_2) and the lowest in aspen plantations (1.5 t CO_2) respectively. Reference source [136] cites similar level of carbon dioxide absorption (1.5–1.8 t) for the formation of 1 t of wood. So, the tree species by their carbon sequestration efficiency can be ranked in the following descending order: oak, birch, black alder, pine, spruce, aspen.

Thus, oak, birch and black alder have the highest carbon sequestration efficiency, pine, spruce and aspen possess the lowest one.

To estimate carbon sequestration efficiency of stands we have calculated the carbon stock per 1 ha across tree species. The stemwood stock values were taken from [96] for growth class II which is the prevailing one in Belarusian forests (averaging 1.6 or II). The calculations were made by clear-cut ages for forest group II (medium cutting age established for tree species in the Republic of Belarus) which make 90 years for pine, 45 years for aspen, 55 years for black alder, 65 years for birch, 110 years for oak. The calculations allowed us to obtain the carbon balance by the tree species and carbon sequestration efficiency of stands on the condition that soft-wooded broadleaved species are replaced by coniferous and hard-leaved ones.

Data on carbon sequestration efficiency are given for clear-cut ages of aspen (45 years), i.e., the age by which no clear cutting has been done yet.

As can be seen from Tables 36–40 the rank of stands by their carbon sequestration efficiency is slightly different from that by tree species: oak, black alder, birch, pine, aspen, spruce.

Table 36

Carbon sequestration by tree stands at the clear-cut age by aspen (45 years)

Indicators	Tree species						Carbon balance ± tC/ha	
	pine	spruce	oak	birch	black alder	aspen	no wood harvest	wood harvest
Stock, m^3/ha	63.5	246.6	210.1	246.6	296.4	284,2	–6.8	84.0
Carbon content in phytomass, tC/ra	100.3	85.9	124.1	105.2	121.1	90.8		

Table 37

Carbon sequestration by tree stands at the clear-cut age by black alder (55 years)

Indicators	Tree species						Carbon balance ± tC/ha	
	pine	spruce	oak	birch	black alder	aspen	no wood harvest	wood harvest
Stock, m^3/ha	300.0	291.0	239.0	263.0	320.0	28.0		
Carbon content in phytomass, tC/ra	114.2	102.6	141.1	112.2	130.7	8.9	236.8	106.1

So, oak and pine have the same ranks whereas the other species demonstrate different ranks. Black alder is ranked second instead of birch, spruce has descended to the lowest rank.

Table 38

Carbon sequestration by tree stands at the clear-cut age by birch (65 years)

Indicators	Tree species						Carbon balance ± tC/ha	
	pine	spruce	oak	birch	black alder	aspen	no wood harvest	wood harvest
Stock, m^3/ha	353.0	356.0	284.0	290.0	363.0	90.0	–	363.0
Carbon content in phytomass, tC/ra	134.3	125.5	167.7	123.7	148.3	28.8	126.7	275.0

Table 39

Carbon sequestration by tree stands at the clear-cut age by coniferous forests (90 years)

Indicators	Tree species						Carbon balance ± tC/ha	
	pine	spruce	oak	birch	black alder	aspen	no wood harvest	wood harvest
Stock, m^3/ha	460.0	488.0	380.0	134.0	210.0	261.0		
Carbon content in phytomass, tC/ra	175.0	172.0	224.4	57.2	85.7	83.4	345.1	81.5

Table 40

Carbon sequestration by tree stands at the clear-cut age by hard-leaved forests (110 years)

Indicators	Tree species						Carbon balance ± tC/ha	
	pine	spruce	oak	birch	black alder	aspen	no wood harvest	wood harvest
Stock, m^3/ha	98.0	45.0	438.0	227.0	320.0	126.0		
Carbon content in phytomass, tC/ra	37.2	15.9	258.6	96.8	130.7	40.3	43.9	–84.0

Carbon balance table 41 has been estimated as a difference between sequestered carbon amounts in phytomass of coniferous and hard-leaved stands and soft-wooded broadleaved ones. The plus sign designated positive effect of sequestration, the minus sign indicates non-effect. Before wood harvest the carbon balance shows that stemwood has not been cut yet and is recorded; after wood harvest it is not recorded.

Table 41

Carbon balance when soft-wooded broadleaved species are replaced by coniferous and hard-leaved ones (optimization of tree species structure)

Clear-cut age, years	Carbon balance, tC	
	no wood harvest	wood harvest
45	–6.8	84
55	106.1	236.8
65	126.7	275.0
90	345.1	81.5
110	43.9	–84.0

Table 41 shows that coniferous and hard-leaved species have higher carbon sequestration efficiency than soft-wooded broadleaved ones before the clear-cut age for oak (110 years).

After wood harvest in coniferous and hard-leaved stands the carbon sequestration effect from the optimization is declining starting from 110 years. We have estimated the effect from further planting of coniferous and hard-leaved tree species (Tables 42, 43).

Table 42

Carbon sequestration by stands at the age of 120 years

Indicators	Tree species						Carbon balance ± tC/ha	
	pine	spruce	oak	birch	black alder	aspen	no wood harvest	wood harvest
Stock m^3/ha	154	104	29	263	42	164		
Carbon content in phytomass, tC/ha	58.6	36.7	17.1	112.2	17.2	52.3	–69.3	–

Table 43

Carbon sequestration by stands at the age of 130 years

Indicators	Tree species						Carbon balance ± tC/ha	
	pine	spruce	oak	birch	black alder	aspen	no wood harvest	wood harvest
Stock m^3/ha	212	183	107	290	107	231		
Carbon content in phytomass, tC/ha	80.7	64.5	63.1	123.6	43.7	73.8	–32.8	90.8

As can be seen from Tables 42 and 43, positive carbon balance will be observed at the age of 130 years when birch stands are clear-cut for the second time. We have calculated carbon sequestration effect (second cutting cycle for coniferous stands) for 180-year period (Table 44).

Table 44

Carbon sequestration by stands (second cutting cycle, 180 years)

Indicators	Tree species						Carbon balance ± tC/ha	
	pine	spruce	oak	birch	black alder	aspen	no wood harvest	wood harvest
Stock m^3/ha	460	488	380	246	15	261		
Carbon content in phytomass, tC/ha	175.0	172.0	224.4	104.9	6.1	83.4	377.0	113.4

As can be seen, the carbon sequestration effect will be higher during the second cutting cycle of coniferous stands (second cycle) than that of broadleaved ones. Afterwards, the carbon sequestration efficiency of coniferous stands will decline again.

During the second cutting cycle of birch stands (Table 43) the carbon sequestration efficiency of coniferous and hard-leaved species is higher than that of soft-leaved ones. In view of this, we have estimated the carbon sequestration effect for coniferous and hard-leaved stands by the clear-cut age of 100 years and that of 50 years for soft-wooded broadleaved stands (Table 45).

Table 45

Carbon sequestration by stands at the age of 100 years (wood harvest of soft-wooded broadleaved species at the age of 50 years)

Indicators	Tree species						Carbon balance ± C/ha	
	pine	spruce	oak	birch	black alder	aspen	no wood harvest	wood harvest
Stock m^3/ha	492	527	412	246	297	288		
Carbon content in phytomass, tC/ha	187.2	185.8	243.3	104.9	121.3	92.0	298.1	

Table 45 proves that the highest carbon sequestration efficiency could amount to 298.1 tC on the one hand. On the other hand, a new forest-growing cycle would start after clear cutting and the effect would remain stable provided that tree species structure was optimized and the negative carbon sequestration effect in coniferous and hard-leaved stands at the age of 110–130 years was eliminated.

It should be noted that optimization of tree species structure will enhance the carbon sequestration efficiency of Belarusian forests regardless of clear-cut ages.

The optimization of tree species structure has been dwelled upon in many research papers [139, 122, 141] which recommended the following optimal tree species structure for Belarusian forests (Table 46).

Table 46

Optimal tree species structure of Belarusian forests

Optimal forest structure, %									
Coniferous			Hard-leaved			Soft-wooded broadleaved			
Pine	Spruce	Total	Oak	Ash and other	Total	Birch	Black alder	Aspen and other	Total
By data of F.P. Moiseenko									
60,0	15	75	5.0	–	5.0	8.0	7.0	5.0	20.0
By data of i.D. Yurkevich									
61.5	12.3	73.8	6.5	1.4	7.9	7.5	6.8	4.0	18.3
By data of A.D. Yanushko									
62.4	15.4	77.8	6.6	0.7	7.3	5.8	7.2	1.9	14.9
By data of O.A. Atroshchenko									
58.3	14.2	72.5	4.7	–	4.7	11.1	7.6	0.9	19.6
3.2% – other tree species									
The existing forest structure by tree species (the Ministry of Forestry of the Republic of Belarus)									
50.8	10.4	61.2	3.7	–	3.7	21.7	8.1	2.1	31.9
3.2% – other tree species									

Table 46 demonstrates that it is recommended by all experts to increase the share of pine, spruce and oak by reducing the shares of birch, black alder and aspen in order to optimize the tree species structure.

To estimate the carbon sequestration efficiency from the optimization of tree species structure, we have calculated the carbon sequestration effect from the implementation of the Program for the optimization of forest structure developed by the Ministry of Forestry of the Republic of Belarus (Table 46). To make the calculations, regularities of carbon accumulation have been used (Table 36).

As can be seen from Table 47, the optimization of forest structure by the Ministry of Forestry of the Republic of Belarus will not result in substantial changes of carbon balance in forests (negative divergence – less than 1% of the total carbon content in phytomass of Belarusian forests).

Table 47

Carbon sequestration by stands after the optimization of tree species structure

Indicators	Tree species (in the numerator – stock, m3/ha at the age of 90 years, in the nominator – tC/ha)					
	pine	spruce	oak	birch	black alder	aspen
Area of the forests under optimization ± ha/%	532435 / 7.4	273669 / 3.8	69927 / 1	–755223 / –10.5	–37514 / –0.5	–83654 / –1.2
Stock, m^3/ha at the age of 90 years, growth class 1.6	263.5	243.6	210.1	246.6	296.4	284.2
Carbon content, thousand tC	+53382.9	+23499.7	+8675.4	–79430.5	–4498.6	–7595.2

The carbon balance is equal to – 5966.3 thousand t or 0.86% of the total carbon amount in Belarusian forests when soft-wooded broadleaved species are replaced by coniferous and hard-leaved ones.

This will occur on the condition that aspen stands have not been clear-cut. If they are to be clear-cut, the carbon balance will turn positive. The carbon balance between the tree species (pine, spruce, oak) that have replaced the soft-wooded broadleaved (birch, aspen, black alder) is – 5966.3 thousand t. If we exclude the sequestered carbon as a result of clear cutting of ash stands aged 45 years, the balance will make up (85558 thousand tC – 83929 thousand tC) + 1628,9 thousand tC.

The above data allow us to justify the formerly made conclusions about the carbon sequestration efficiency from the optimization of trees species structure of Belarusian forests.

In spite of the local measures taken in the forests of Belarus, the main criterion of positive carbon balance is the “Golden rule of forest use” saying that the annual wood harvest should be lower than the annual wood increment. So, as of 01.01.2017, total average change in wood volume was estimated at 32.6 million m3, the wood harvest being 21.07 million m3. If the average conversion factor to transfer wood volume into weight (t) of sequestered carbon is taken as a weight-average factor across the tree species structure of Belarusian forests and set to – 0.3898, it can be calculated that in 2016 forests of Belarus deposited 12707 thousand tC, the carbon content in harvested wood was 8213 thousand tC. Carbon balance amounted to +4494 thousand t in 2016. At the same time it should be noted that annual current stock changes in Belarusian forests [133] tend to grow.

It should be mentioned that the Strategic Development Plan for the Forest Sector for 2015–2030 [131] envisages the share of pine on the forested lands to amount to 60% (58.3% as prescribed by the Program for the optimization of forest structure [139]).

However, if the Program is to be implemented at the current rate, annually birch stands should be replaced by pine ones on an area 35 496 ha.

Until 2030 forest plantation fund is expected to range from 29 810 ha (2016–2020) to 37 320 ha (2026–2030) annually. As can be seen, the optimization will affect areas larger than the estimated forest plantation fund. We estimate that these actions can be implemented over a longer period of time without violating silvicultural-ecological requirements to forest utilization.

It is known that for 2016–2020 the annual forest plantation fund will amount to 6 886 ha for birch forests [131].

It will amount to 8 334 ha in the second five-year period and 8 621 ha in the third five-year period (2026–2030).

If assumed that 80% of the area will be replanted by pine as envisaged by the Program for the optimization of forest structure [139], the areas will annually amount to: for 2016–2020 – 5 509 ha, 2021–2025 – 6 667 ha, 2026–2030 – 6 897 ha. Thus the optimization of forest structure will affect the area of 27 545 ha, including: for 2021–2026 – 33 335 ha, for 2026–2030 – 34 485 ha. The total area for 2016–2030 is estimated at 95 365 ha or annual average of 6 358 ha. The share of pine will be respectively increased in the following way: for 2016–2020 by ≈ 0.4%, for 2021–2025 – 0.5%, for 2026–2030 – 0.5%. The total increase in share will amount to 1.4%. The share of birch stands will be reduced by the same amount respectively. Therefore, some amendments should be made to the Strategic Development Plan for the Forest sector for 2015–2030 [131]:

– 2015–2020 – share of pine – 50.6%, share of birch – 22.7% of the forested lands;

– 2021–2025 – share of pine – 51.1%, share of birch – 22.2%;

– 2025–2030 – share of pine – 51.6%, share of birch – 21.7%.

In view of the above, we must conclude that:

– tree species have different carbon sequestration efficiency. The largest carbon content per 1 m^3 of phytomass is registered for oak, birch and black alder, the smallest one – for pine, spruce and aspen. These values should be considered when choosing felling sites;

– wood stock per 1 ha and age of stands should be considered for the estimation of carbon sequestration efficiency;

– optimization of tree species structure in Belarusian forests will lead to their improved carbon sequestration efficiency;

– maximization of carbon sequestration by phytomass of Belarusian forests requires clear-cut ages to be changed as follows; 100 years for coniferous and hard-leaved species and 50 years for soft-wooded broadleaved ones;

– the rates of optimization of tree species structure in Belarusian forests should be reconsidered in terms of the predicted forest plantation fund over the optimization period.

6.3. Evaluation the level of organic carbon depositing by forest soils

Organic carbon content in the forest floor has been estimated by the methodology described in reference source [6].

Table 48

Accumulation of organic carbon in forest floor of Belarusian forests

Predominant tree species	V_{sw} –stemwood volume, m^3/ha	Forest area by tree species, ha	Organic carbon content in forest floor	
			thousand tC	%
pine	238	4144589	45176,0	79,8
spruce	255	769665	8081,5	14,3
oak	180	284334	654,0	1,2
birch	173	1909689	1336,8	2,4
black alder	195	707211	565,8	1,0
aspen	201	183967	110,4	0,2
other	133	259961	623,9	1,1
Total		8259416	56548,4	100,0

Table 48 gives volume by tree species as average for the forests of Belarus as of 01.01.2017. The same applies to the forest areas by tree species.

As can been seen from Table 48, the largest amount of carbon is contained in the forest floor of pine and spruce forests (94.1%) as they occupy larger share in the tree species structure and due to slower decomposition of the forest floor in pine and spruce forests (142 and other).

Organic carbon content in the forest soils has been estimated by the methodology described in reference source [6]. Areas of forest types are taken from [133].

Table 49

Accumulation of organic carbon in forest soils of Belarusian forests as of 01.01.2017

Forest type series	Area		Carbon content in soils		
	ha	%	tC/ha	thousand tC	%
Lichenous	20293	0.25	16.92	343.4	0.04
Heather	191446	2.32	16.92	3239.3	0.35
Vaccinium	14596	0.18	18.40	268.6	0.03
Mossy	1715788	21.14	31.01	54128.4	5.84
Bracken	1203000	14.57	40.55	48778.7	5.26
Wood-sorrel	1231118	14.92	61.59	75823.1	8.18
Myrtillus	1265686	15.32	87.4	110669.1	11.95
Long-mossy	405717	4.91	261.51	106098.4	11.45
Ledum	111073	1.34	274.35	30472.9	3.29
Sedge	439461	5.32	235.05	103295.3	11.15
Sphagnum	10067	0.12	235.05	2366.2	0.26
Sedge-sphagnum	176311	2.13	254.18	47372.6	5.11
Aegopodium	258568	3.13	144.81	37443.2	4.04
Urticaceous	131680	1.59	489.36	64438.9	6.95
Ferny	605148	7.33	228.75	138427.6	14.95
Riverine-grassy	55625	0.67	262.35	14593.2	1.57
Hair-grassy	1750	0.02	228.75	400.3	0.04
Riverine-floodplain	10379	0.13	18.40	190.9	0.02
Grassy-floodplain	8949	0.11	66.69	2350.2	0.25
Alder-floodplain	4191	0.05	228.75	958.7	0.10
Ash-floodplain	356	0.005	144.81	51.6	0.01
Forbs-floodplain	1705	0.02	144.81	246.9	0.03
Floodplain	7799	0.09	18.40	143.5	0.02
Swampy-forbs	135	0.003	228.75	30.9	–
Meadowsweet	216808	2.62	228.75	49594.8	5.35
Sedge-grassy	91162	1.10	254.18	23171.6	2.50
Swamp-ferny	40447	0.49	228.75	9252.3	1.00
Iridaceae	5417	0.06	228.75	1239.1	0.13
Willow	4628	0.06	254.18	1176.3	0.13
Grassy	113	0.002	228.75	25.8	–
Total	8259416	100.00	5160.92	926591.8	100.0

As can be seen from Table 49, forest types with the maximum level of greenhouse gases absorption include urticaceous forest types series (489.36 tC/ha), ledum (274.35), long-mossy (261.51), etc.

The largest carbon accumulation is registered in ferny (14.95%), myrtillus (11.95%), long-mossy (11.45%) and sedge (11.35%) forest types series, i.e., forest types with semihydromorphic and hydromorphic soils.

It should be concluded that:

– the share of forest floor in carbon sequestration amounts to 3.4% of the total carbon content in phytomass and soils;

– essential share of carbon sequestration (94.1%) is contained in the forest floor of coniferous stands;

– the maximum level of carbon dioxide absorption is revealed in urticaceous, ledum, riverine-grassy, long-mossy and other forest types.

6.4. Recommendations for optimum species structure of forest fund with structure to maximize the level of carbon dioxide absorption

In order to increase the carbon dioxide absorption by tree species the following factors should be taken into consideration:

– the choice of trees for improvement felling should be based upon the biological features of tree species in terms of their carbon sequestration efficiency;

– evaluation of carbon sequestration efficiency of stands should take into account the wood stock per 1 ha and clear-cut age;

– optimization of tree species structure of Belarusian forests [9] will lead to their improved carbon sequestration efficiency;

– carbon sequestration effect from the optimization of tree species structure can be maximized by re-establishing the clear-cut age for coniferous and hard-leaved stands at 100 years for forest group I, for soft-wooded broadleaved at 50 years;

– due to global climate change impacts, in particular in the southern regions of Belarus [5], and adverse weather effects of 2016 it is recommended to do extensive environmental and biological studies in order to develop measures on increasing forest sustainability on the affected areas;

– in order to improve the efficiency of tree structure optimization it is advisable to develop a software package based on GIS "Forest Resources" that can be used to estimate carbon sequestration efficiency of planned forest plantations;

– the extent of tree species optimization (replacement of pine by birch [131]) should be revised as it is set too high.

The following long-term measures are to be taken in order to increase the level of carbon dioxide absorption in the Republic of Belarus (Table 50).

Table 50

Measures on the optimization of the tree species structure in the forest fund of the Republic of Belarus

No.	Description of measures	Implementation by stages		
		2018–2020	2021–2025	2026–2030
1.	To develop recommendations for improving sustainability of Belarusian forests	+	+	–
2.	To develop a software package based on GIS "Forest Resources" that can be used to estimate carbon sequestration efficiency of planned forest plantations	+	+	–
3.	To optimize tree species structure of forests across prevailing tree species (share in forested lands):			
	pine	50.6	51.1	51.6
	birch	22.7	22.2	21.7

According to Table 50, the share of pine forests will amount to 51.6% until 2030, that of birch forests to 21.7%.

On the whole it should be noted that the optimization of tree species structure of Belarusian forests will lead to their higher economic efficiency on the condition that ecologically sound and socially-oriented forest management and forest utilization are ensured.

7

INTERNATIONAL PRACTICES OF INCREASING OF THE LEVEL OF CARBON DIOXIDE ABSORPTION

7.1. Review of best international practices of increasing of the level on greenhouse gases absorption by sinks (forests, swamps)

Forests of the planet and their role in the global carbon cycle are taking on greater importance from year to year. Industrial progress, burning of fossil fuels, cutting of forests and other anthropogenic activities have resulted in carbon imbalance. This fact is of great global concerns, so numerous measures are taken to mitigate climate change impacts caused by anthropogenic activity all over the world. Forests are natural stabilizers of the atmospheric composition due to the photosynthetic CO_2 capture by their vegetation. They contain nearly 80% of carbon absorbed by terrestrial biota. Over the past decades, the global forests have absorbed about 30% of annual anthropogenic emissions, the same share was captured by the world oceans. The level of CO_2 absorption by forests considerably differs across different countries (Figure 15).

However, nowadays we can observe only early stages of the development and implementation of measures to mitigate climate change impacts through carbon accumulation, its emission reduction by forest ecosystems and forestry adaptation [143–151].

International practice offer several strategies for absorption and retention of carbon by forests. They include:

– conservation of the existing forests and growing of new ones (retention of the accumulated carbon in the form of biomass and soil carbon of the existing forests, including old-aged ones; prevention of reduction of forested areas, increasing of nature protection areas; protection of forest stands; forest-growing on degraded lands);

– improvement of forestry operations aimed at increasing the level of carbon absorption (increasing of wood volumes by changing the cutting cycles and the frequency of improvement fellings; increasing of increment in forest stands, incl. fertilizers use; use of environmentally friendly cutting and logging techniques, etc.);

– substitution of materials and fossil fuels (using wood to produce long-life products and structures instead of energy-consuming concrete, steel and other materials and reducing fossil fuel demand in this way; improvement of woodworking technology; using wood as fuel, including logging and woodworking residues used for biofuels production, etc.).

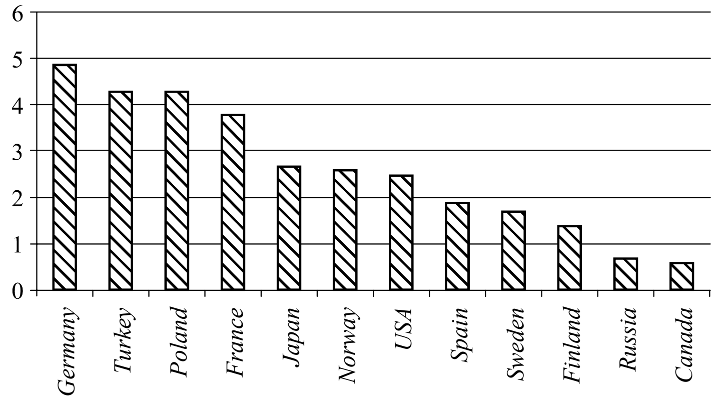

Figure 15. **Level of CO_2 absorption by forests in industrialized countries, t/ha**

Essentially these strategies match to sustainable forest management (Figure 16) [148, 151, 152].

The studies using climate change models give controversial results. If we assume that mature forests will remain pure CO_2 sinks in future, the nature protection strategies are quite appropriate. If they become carbon sources, increasing of wood harvest is more promising. Therefore, we must adhere to the strategies aimed at increasing both wood volumes and wood harvest, until reliable data are not accessible [151].

Estimation of carbon sequestration by forests in Central Europe proves that climate change will primarily have negative impact on carbon accumulation. Climate warming will cause forest productivity to be balanced by losses due to forest pests, diseases and other adverse factors (about 45% of increment). Review of the numerous studies has shown that climate change and associated increasing forest damage by fires, windblows and pests can reduce their carbon sequestration capacity (by 38.5%) and other environmental functions with simultaneous increase in biodiversity (by 35.6%) [153, 154].

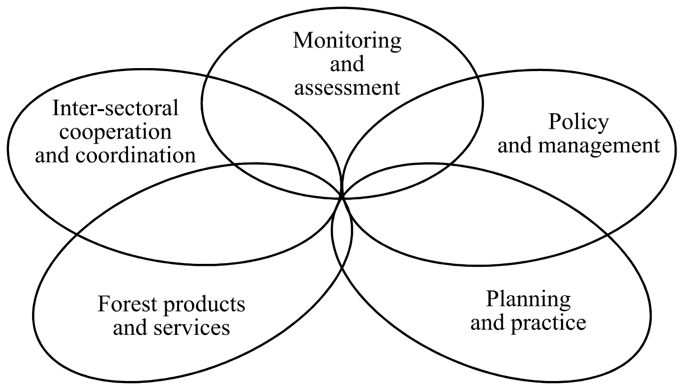

Figure 16. **Comprehensive approach to sustainable forest management**

Long-term measures on greenhouse gases emission reduction can prove to be economically ineffective in the short-term perspective which has a strong impact on urgent measures to reduce emission [155, 156].

Carbon balance can be maintained by the increase in forest cover. Forests are of great economic and ecological importance for our planet. These factors are fundamental to forest policies of many countries in the world [157].

The forest cover of most European countries, apart from Austria, Slovenia, Finland and Sweden, varies from 20 to 40%. It comprises about 10% in the Netherlands, Denmark and Ireland. The forests of Europe cover 44% of its total area, i.e., nearly 1 billion ha. Nearly 80% of the forests are located in Russia. Accessibility of forests for logging operations ranges from 80 to 90% of their area, in Eastern Europe it makes up 40%. For the last 15 years the forest cover in Europe has increased by 13 million ha (that is comparable to the area of Greece) due to forest-growing and natural reforestation on lands withdrawn from agriculture. Many experts claim that 74% of forest have been damaged by anthropogenic impacts, of which about 70% of forests are semi-natural, nearly 4% are man-made. The remaining 26% of forests are low-damaged forested areas in remote and hardly accessible regions of Eastern and Northern Europe as well as in Russia. Wood stock in forests is also increasing. Over the past 20 years it has grown by 8.6 billion m^3 and amounted to 112 billion m^3 which is equal to the wood stock in the forests of France, Germany and Poland taken together. Annual increment is estimated at average 358 million m^3 or the total wood stock in Slovenia. The increase in wood stock outperforms that of forested areas which means that wood increment per a unit area may result from both adequate forest management and changing stands quality in the course of time [148, 158–161].

On average the European forests absorb about 10% of the total CO_2 emission. Most European forests (98%) are managed in accordance with sustainable management principles. Conservation forests are of crucial importance for maintaining the carbon balance, thus, their area annually increases (by 0.5 million ha per annum). The largest areas of conservation forests have been allocated in Germany, Norway, France, Great Britain, Spain, Sweden Poland, Austria, Italy and Finland. Norway invests by far more funds into the conservation of forests in developing countries (they consider it to be the fastest and cheapest way of global warming prevention) than any other country of the world (for instance, they invested one billion USD for these purposes in 2010–2012). In Switzerland over 60% of forests are under protection [153, 161–185].

An important issue is the regulation of forestry operations on nature protection areas and their recreational uses. In foreign countries forests can be both state- and privately-owned, so types and extent of forestry operations on the areas under protection are prescribed by law together with the owner's liabilities to carry out necessary improvement operations. If land users fail to fulfill their obligations, certain sanctions may be imposed upon them. Privately-owned forests are often assigned the status of conservation forests in a mandatory manner with appropriate subsidies being paid to the forest owners by the government. In spite of the resulting restraints of forest utilizations, terms and ways of forest regeneration, many forest owners regard the status of conservation forest as highly beneficial as they get governmental funds to take necessary actions. Commercial uses are prohibited on nature protection areas. In Germany clear cutting in conservation forests can be carried out only if authorized by relevant government bodies. In Swiss in conservation forests any activity is prohibited, fellings and stump removal require special permit. Forest cuts are not allowed in nature protection areas in Austria [148, 166–170].

All Western European countries have effective legislation in the field of forested areas protection. The nature protection is regulated by both domestic and EU laws. Sweden, Norway and Finland have particularly strict laws. Sustainability of forestry in Finland is ensured by National Programs of the forest sector and laws (since 1923) that prohibit any destruction of private forests. If the forest owner fails to take necessary after-cut regeneration actions, he is temporarily ceased the right of forest exploitation and lawfully charged with funds necessary to complete the regeneration activities. On the other hand, the government provides financial assistance or loans to the forest owners who ensure ongoing wood growth and proper forest care [162, 164, 166, 168, 171–173].

Several studies prove that carbon sequestration is more intensive (by 48%) in managed forests rather than in conservation forests. At the same time, conservation forests have soil carbon stock twice the same amount as managed forests, in spite of the fact that managed forests have better capacity for soil carbon accumulation due to the fact that soil damage during cutting operations results in enhanced carbon losses. It has been established that even 800-year-old forests can serve as carbon sinks. According to recent research data, forests growing on the islands of Northern Sweden for thousands of years still deposit carbon in the soil horizon. In such forests more than 90% of carbon is fixed by soils. The carbon stock structure dynamics in black spruce stands of Alaska has proved that carbon content in biomass reaches its maximum after 200 years, however the total carbon stock continues to grow even after 500 years due to its sequestration by soils (Figure 17) [152, 174–176].

Important factor that encourage carbon stock are forest growing and forest regeneration. In 2010 nearly 7% of global forests were of man-made character. Man-made forest regeneration is preferred by siviculturists of Ireland, Denmark, Belgium, the Netherlands because it makes it possible to create new forest plantations from high-quality trees. In Denmark the share of forest plantations makes up over 30% of the total forested area, in Ireland and Belgium it takes the largest half. Forest growing on former agricultural lands enhances the carbon content in soil [148, 174].

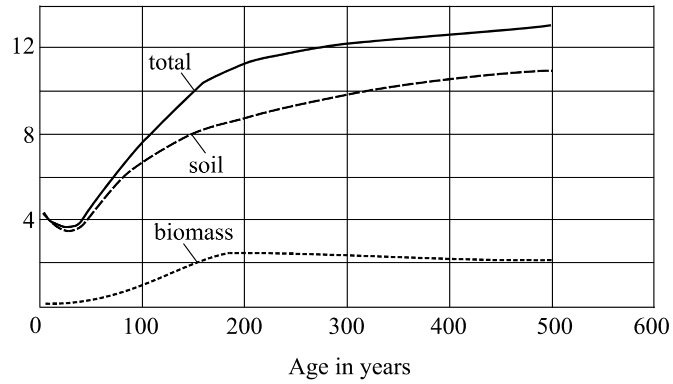

Figure 17. **Carbon stock structure dynamics in spruce stands**

Large volumes of wood together with the carbon contained in it are removed from the forest during wood harvest. Considerable amount of carbon is present in leaf and branch shedding, forest floor and soil. As a result of clear-cutting they get more access to light, heat and oxygen, in particular, when soil cover and upper soil layer are considerable damaged. Decomposition is accelerated causing increased carbon dioxide emission. As a result, Swedish felling sites remain net sources of carbon even after 15–20 years upon cutting (even though new forest plantations were created on the sites). Two decades may be required for carbon sequestration by young forest to outperform the soil carbon emission. Complete restoration of carbon balance after cutting operations may take 30–40 years. Clear-cut forests and soil-cultivated forest plantations lose significant amount of carbon during each cutting cycle. As the forest grows, the carbon stock begins to increase too, however, it is never replenished to the level of carbon amount in untouched forest by the time of the next clear cutting. Natural forest regeneration, minimum soil cultivation or minimum (no) soil impacts (for instance, selective cutting in differently-aged stands) result in smaller carbon loss. It is recommended to avoid damage or mixing of the upper soil layer in order to maintain soil biodiversity and productivity. This can be achieved by leaving minimum 25 trees per 1 ha evenly scattered over the felling site (tree diameter should be larger than 15 cm). For felling sites with nutrient-poor soils it is advisable to leave 50 trees per 1 ha. All old stumps and stumps thinner than 15 cm must also be left. Trees left must belong to different species [152, 177–180].

Gradual cuttings have a different effect on carbon flows than clear cuttings. If woody vegetation is left on the ground to a greater or lesser extent, major carbon emission can be avoided. Total amount of carbon dioxide emission by forest only slightly affected when small volume of biomass is removed because the trees remaining on the felling site begin to grow more intensively. This makes us conclude that cancellation of clear cutting is beneficial to climate in spite of the fact that young tree growth is more intensive than that of the remaining mature trees. Carbon stock in forests where no clear cutting takes place is higher. Studies of the mountain forests in Central Europe prove the fact that gradual and selective cuttings are more effective when logging operations do not affect carbon sequestration in a great extent. However, it should be kept in mind that gradual and selective cuttings are more challenging, harvesting of logging residues is more costly which has a negative effect on substitution of fossil fuel by wood [152, 153, 177].

Improvement fellings have inconsiderable impact on carbon balance. As a rule they do not cause any increased carbon emission. To maximize the carbon stock it is highly important to make them more regular. Computer modelling has proved that 20% more frequent improvement fellings result in the increase in biomass carbon content by 13%, in soil – by 10% over one-hundred-year period. 10% less intensive cuttings in Swedish forests can enhance carbon stock by 60% by 2030. No other forestry operations are able to have similar effect on carbon budget over such a short period of time. Longer intervals of improvement fellings reduce the volume of harvested timber and logging residues for biofuel production. Biofuel serves as a substitute for fossil fuels thus reducing carbon dioxide emission. Shorter intervals of improvement fellings reduces the emission to a greater extent than can be achieved in the long-term (100-year) perspective. More frequent improvement fellings are recommended for spruce forests to improve their resistance and reduce pest damage. The improvement fellings must take place in winter or summer during precipitation-free periods. High density of spruce stands must be ensured [170, 178, 181].

Silvicultural approach that combine more frequent and less intensive improvement fellings lead to increased carbon stock in forests and reduced emissions. Research findings show that a strategy aiming at maximum wood yield per one unit area at all costs is not effective from the climate point of view [170].

It should be taken into account that strategies geared towards improved carbon sequestration capacity of forests are time-limited. The carbon stock cannot increase for ever. Besides as the time passes, there is an increasing risk of carbon emission due to nature impacts of catastrophic character [152].

The choice of tree species is crucially important for the forest to adapt to climate change as well as for the carbon balance to be maintained. Spruce and birch forests accumulate more carbon in their soils than pine forests do. This can be explained by higher organic nitrogen content in spruce and birch shedding than that in pine. In northern Sweden, soils of spruce and birch forests contain 65% more carbon than those of pine forests. In southern regions this difference is half as much and makes up 33%. Higher carbon sequestration capacity of soils in several regions of Sweden can be attributed to large shares of spruce and birch thus providing good prospects for future improved carbon sequestration capacity of forests. Apparently, summer months in southern regions of Sweden are characterized by hotter and drier weather than in the northern parts. It means pine is a tree species of choice for many regions. It is less sensitive towards windstorms than spruce but demonstrates lower carbon sequestration capacity than spruce and birch. Many studies show that soft-wooded broadleaved forests accumulate more carbon than coniferous ones. However, the coniferous stands have larger carbon accumulation capacity [174].

More frequent damage and loss of forests occur due to fires, windblows and pests caused by climate change impacts. These adverse events largely affect pure-structured, evenly-aged forest stands, primarily composed of spruce and other coniferous species, so, the prospects of their growing are very unclear. Significant forest management measures are required to resist pest attacks. Therefore it is advisable to transfer to tree species that are more draught-resistant. Multistoreyed and mixed forest plantations are recommended as well. Resistance of spruce forests can be improved by adding other tree species and increasing their share in the stand structure (optimal share 50%). More frequent improvement fellings significantly enhances resistance of spruce forests.

One of the techniques of intensive forest growing is extensive use of fertilizers and introduced species. In future, intensive forest growing may require about 1 500 kg/ha of nitrogen fertilizers to be applied during one cutting cycle (nowadays about 150 kg/ha is applied 10 years prior to cutting). Experiments show that if 600–1 800 kg/ha of nitrogen are introduced into the forest soils for 14–30 years, carbon sequestration increases by average 25 kg per 1 kg of nitrogen. Soil carbon amount also goes up (by 11 kg per 1 kg of nitrogen). Phosphorus and potassium fertilizers cause carbon sequestration increase of 38 kg by trees and 11 kg by soils. Even if the production of fertilizers is associated with greenhouse gases emission equivalent to 0.4–1.2 kg of carbon per 1 kg of nitrogen, the climate effect from their application still remains positive. Multiple fertilizers application in spruce forests results in increased carbon amount by 26% by the time the forests approach the felling age as compared to similar surrounding stands where no fertilizers have been applied. Application of fertilizers increases wood volumes by 80%. It also reduces output of logs but yields more raw materials for pulp and biofuel production [174, 181, 188, 189].

In Sweden about 15% of forests can be subject to intensive forest management such as application of fertilizers and use of highly productive hybrid species of spruce and other trees. Intensive forest growing will make it possible to increase annual carbon sequestration by 3.8 Mt for 2030–2040 as compared to ordinary forest management practices [189].

However, Sweden has no experience of large-scale and long-term intensive forest growing that involves significant risks. In particular, multiple application of fertilizers affects tree species structure and other forest vegetation. Besides, no experimental techniques have been developed to measure carbon flows and to estimate net accumulation of carbon by forests where fertilizers have been applied for many years [174, 177].

Intensive forest growing leads to the formation of homogenous populations and reduced forest diversity that enhances the risk of forest pest damage and diseases as well as reduces forest resistance to climate changes. Nowadays there are no available science-based data to perform quantitative assessment of the above risks. Application of fertilizers bears the risk of expansion of some pathogens, e.g., Scots pine blister rust (*Cronartium flaccidum*) and snow blight (*Phacidium infestans*). If fertilizers are applied in rot-affected forests, this can cause intensive development of mottled butt rot and make the forest less resistant to windblows [190].

There is a direct correlation between nitrogen content in soils and emission rate of nitrogen oxide. If nitrogen fertilizers are applied, emission of nitrogen oxide by forest soils can increase. There are some indirect effects of fertilizers application that affect greenhouse gases emission. For instance, fertilizers can penetrate lakes and streams that are present in the forest landscape. There are no available data that could be used to make quantitative assessment of these impacts [174, 188].

Many research findings prove that nitrogen fertilizers reduce the methane-decomposing capacity of forests. However, there are numerous opposite views. Apparently, low increase in nitrogen concentration in forest soils does not affect the oxidation of methane, so methane emission will not be significant [152].

Firewood production has almost tripled in Sweden over the last decade. In Finland energy uses of woody biomass grew rapidly in the 2000s and amounted to 18.7 million m^3 in 2013 (including 8.7 million m^3 of wood chips) making 10% of the total national energy generation. Most fuel comes from logging residues (branches and tops). Nowadays logging residues are collected on every third clear-cutting site. Wood harvest for energy uses implies removal of biomass from the forests for subsequent burning. Wood destruction and carbon dioxide emission into the atmosphere occur at a faster rate than wood decomposition in the forest. If wood is left in the forest, its small carbon content is eventually transferred to soil. Harvesting of logging residues also involves removal of nutrients from the forest soil, in particular, when they are harvested before the needles fall off the branches. Should the young forest growth slow down, so does the rate of carbon accumulation in biomass. Harvesting of branches from the felling site results in lower productivity of successive generations by 6–32%. When logging residues are harvested from improvement felling sites, the growth rates are reduced by 11–26%. To enhance carbon sequestration, it is advisable that stumps and large roots are harvested along with the logging residues. Harvesting of logging residues and stumps from fertile areas or application of mineral fertilizers can prevent the loss of ecosystems productivity and carbon sequestration efficiency. Calculations made for medium-fertile soils have not demonstrated any loss in productivity because of biomass harvest as compared to the felling site where no biomass was removed [191–198].

In Finland logging residues harvest for energy uses reduces the amount of nutrients, especially in spruce forests, if logging residues (including needles and leaves) are harvested immediately after clear cutting. It is recommended to harvest logging residues in spruce forests only after needles have fallen off, i.e., minimum 2 weeks in May-June and 4 weeks in late summer. If logging residues are collected together with needles (leaves), nearly 30% of the biomass should be left in the forest and evenly spread across the felling site. When logs are harvested during improvement fellings, logging residues can be collected from all sites. If whole trees are harvested, part of them should be left on the felling site. About 30% of the wood harvest (small logging residues, needles, leaves, tree tops, small 1–2 m long logs) are to be left and evenly scattered across the felling site. Needles and leaves should fall off the logging residues in spruce and deciduous forests. In pine forests they must be allowed to dry, however it is less effective in terms of nutrients return as compared to spruce and deciduous forests [178].

Almost 20% of wood biomass comes from stumps; however their harvest is nowadays rather limited. The effect from stump harvest on carbon flows and the environment has not been thoroughly studied yet. There is some ongoing research into this issue but not many related publications have appeared yet. Stump extraction can have strong effect on soils and result in faster decomposition processes and increased carbon emissions. On the other hand, soil layer destruction can assist forest regeneration and have a positive effect on carbon sequestration in the long-term perspective. One of the studies shows that carbon dioxide emissions do not change during the first year upon stump extraction and preparation of forest plantation area. During the second year there is a growing tendency of carbon dioxide emission by soil, however the causes of this phenomenon have not been explained. It has been noted that the surface area affected by tractor wheels or other mechanical impacts is much larger than the area under stump extraction. Heavy consolidation of soil causes reduced carbon dioxide emission and lower degree of drainage that bears the risk of methane emission [177, 194–197].

North America possesses about 255 of the global area of untouched forests. Almost one third of the USA is covered by forests. In Canada forests occupy 50% of the total territory. All provinces and regions of Canada have their own policies and development plans for the system of nature protection areas. This provides an opportunity to take into account natural and social features of the regions and their population needs. Forests of Canada are largely owned by 10 provinces (71%). Each of the provinces has its own forest legislation that regulates forest management, financial and economic issues, forest ownership. In the USA the law stipulates the procedure of general planning, including resource assessment and management of national forests, plans of research projects for the research stations of the U.S. Forest Service, assistance to the U.S. forestry agencies and owner of small forest sites [159, 199–201].

Over the last decades the U.S. forests have been considerably damaged and destroyed (pests, fires, draughts) due to gradual warming (the fastest warming rates have been observed in Alaska and western states over the last 100 years). This can convert the U.S. forests into a source of carbon from a carbon sink that compensates about 13% of greenhouse gases emissions from the fossil fuels extraction. In moderate climate regions of the USA and Canada, the damage and mortality of forests will not be compensated by positive climate impacts on forest growth in the coming decades. Impacts of the increased CO_2 level on mature stands can hardly be predicted, the same applies to climate change impacts on smaller areas or certain tree species. Increased carbon sequestration in the U.S. forest sector results from the expansion of forested areas, forest growing, forest regeneration on felling sites, management of carbon stock in the existing forests (more frequent cutting cycles, increased forest increment, the choice of tree for improvement fellings based on classical silvicultural approaches, etc.). Other factors include energy uses of wood, retention of carbon in wood products replacing other materials that cause large greenhouse gases emissions (concrete, steel, etc.). These strategies offer different opportunities in terms of time and capacity [202–206]. They include sustainable forest management, mitigation of climate change impacts and adaptation to climate change (Figure 18).

Strategy for Research into global change within the forest sector for 2009–2019 has been developed to improve approaches towards ecosystems sustainability (adaptation), increasing of carbon absorption and emission reduction (mitigation), etc. The strategies for mitigation of climate change impacts include: increased carbon absorption by forests, carbon retention in soils, vegetation, long-life wood products and processed wooden materials; indirect reduction of greenhouse gases emission (for instance, by using bioenergy to compensate for emissions from burning fossil fuels); reduction of greenhouse gases emission [207–209].

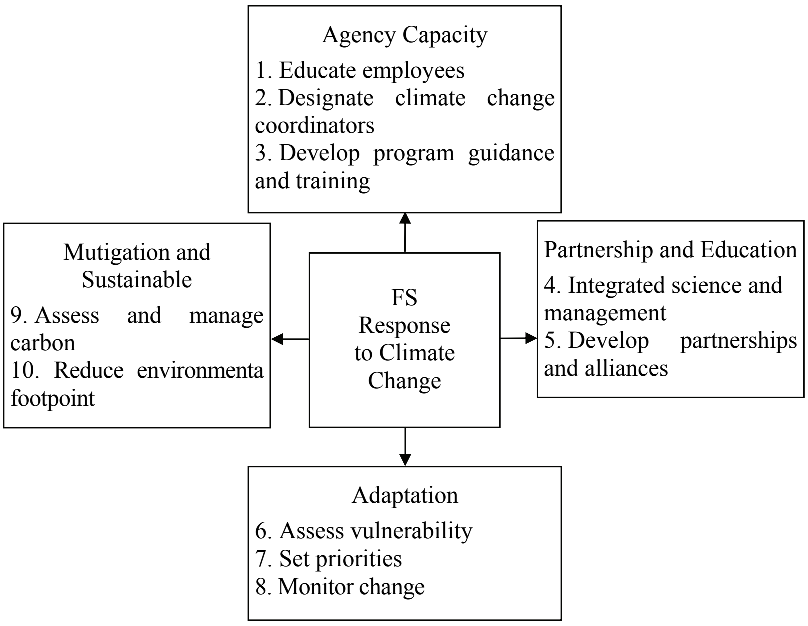

Figure 18. **U.S. forest management policy under climate change conditions**

The priority of national forest policy in Canada is mitigation of climate change impacts through carbon accumulation, reduction of carbon emission and adaptation of the existing approaches towards sustainable forest management. The forest policy is revised and updated every three years. Climate change will reduce the economic benefits from selling traditional timber in Canada. Therefore, they promote wooden products that have added value and expansion of product lines based on research and innovations (for instance, new construction materials, biofuel, bioproducts such as antibiotics, bioactive paper, bioplastics, glues, biopesticides, herbal medicines, biochemical substances, industrial ferments, etc.), non-timber forest resources and recreational forest use, i.e., the development of bioeconomy is under way [199, 210–213].

Climate change is very likely to cause changes in the formation and age structure of forests. It probably makes the preservation of the existing species and ecosystems, their age structure ineffective. Mild winters require extensive forest roads construction which affects soil conditions and water regime. The adaptive capacity of the forest sector to climate change is determined by: awareness of the problem and urgency to solve it; range of solutions to the problem accessible to managers; economic resources; effective management system, including decision-making autonomy; experience, skills and educational background of managers; access to information and risk management skills [199, 210–213].

The cost of new technology should be considered in terms of its efficiency for climate change mitigation, for instance, gene modification to generate trees with higher adaptive capacity to future conditions. At the same time, it can be promising to change the regions of recommended seeds origin for forest regeneration so that the seeds "survive" in the future climate. In some cases the changes can be considerable, for example, replacing of coniferous species by deciduous ones in fire-hazardous regions [199, 210–213].

Some principles or adaptation strategies include the following recommendations: to increase landscape diversity; to maintain biological diversity; to implement management projects for forest ecosystem disturbances: forest regeneration, forest growing, sanitary fellings, etc.; to implement early detection and prompt response strategies; to manage realistic results (projects with high probability of success); to apply adaptive climate change approaches to forest regeneration and forest growing; to develop policies and standards focused on climate change; to predict major forest ecosystems disturbances (draughts, fires, species extinction, changes of ecosystems functions, scenario planning of potential actions) [199, 210–213].

Possible adaptation scenario includes the following measures: alternative plant genotypes or new species in contemplation of future climate if positive findings are available (this will require new approaches to biodiversity conservation); change of regions for the recommended seeds collection for future forest regeneration; use of non-conventional sizes and quality of harvested wood; increased sanitary fellings after forest fires and pest damage; use of climatic variable in the models of growth and productivity, forest management and land use plans, change of land use on some areas (forestry to agriculture and vice versa); reduced felling cycles; forest ecosystems planning to reduce negative impacts of pests and diseases; development and implementation of alternative logging technologies; use of climate change approaches when planning, constructing or modernizing production facilities for processing timber of non-conventional size and quality; public dialogue about the values of forest and forest management under climate change conditions; appropriate forestry operations to control increasing forest fires; updated measures to improve productivity [199, 210–213].

In most provinces, the costs of forest cultivation work are reimbursed, planting stock is provided on a free basis, silvicultural volunteering is encouraged [199, 210–213].

In China, the majority of forests are state-owned (73–74%). The Chinese government carries out a number of the world's largest environmental projects, including projects on conservation forests, regeneration of grass cover on agricultural lands, creation of forest belts, etc. At present the total area of man-made forests in China exceeds 50 million ha making it the world's first ranked country in this field. The extension of forested areas in the Asia-Pacific region can be attributed to the attempts of China in the field of forest cover increase [148].

Studies on how the forest plantations affect carbon sequestration have started only recently. Approaches to plantation silviculture are being developed aimed at maximizing the wood harvest and carbon accumulation. The capacity of bioenergy crops in the field of mitigation of greenhouse gases emissions rely on a number of ever-changing factors: soil, climate, previous land resource management, future land uses, crop yields, carbon stock upon felling, etc. Research into the assessment of soil carbon dynamics done in England and Wales has demonstrated that growing of poplar (*Populus trichocarpa Torr. & Gray × P. trichocarpa, var Trichobel*) will have a positive impact on greenhouse gases emission reduction whereas cultivation of rape and autumn wheat leads to carbon emissions [214, 215].

Swamps cover only 3% of the planet's territory and contain more carbon than all global forests: in boreal zones 7 times as much, in the tropics 10 times as much carbon per 1 ha as ecosystems on mineral soils. Peatlands contain twice as much carbon as all forests in the world. In subarctic regions peatlands cause formation of permafrost.

Dry vegetation and peat have excellent insulation properties that prevent ice from melting in summers. As a result cryogenic underlaying plateaus or peat icy fills are formed as deep as several meters underground. Long-term carbon balance of natural swamps is positive, carbon accumulation varies throughout the year sometimes turning negative. Actually peat swamps approach the transition point between emission and accumulation of carbon making the swamps very sensitive to severe climate changes and anthropogenic impacts. Globally, undrained peatlands (over 3 million km^2) absorb up to 100 Mt carbon per annum [148, 150, 157, 216–218].

Since the Holocene age (almost 12 000 years ago) peatlands have taken in enormous amount of CO_2 from the atmosphere and stored it as carbon. Some experts believe that carbon capture by peatlands is a major cause of the reducing concentration of carbon dioxide and the Ice Age. When peat is formed, a part of dead vegetable matter decomposes in the absence of oxygen causing methane emissions. Natural peatlands are main global source of methane. Methane is a stronger greenhouse gas than carbon dioxide. From the short-term perspective, natural peatlands do not have considerable effect on climate because CO_2 absorption is balanced out by methane emissions. However, methane is removed from the atmosphere at a faster rate (12 years), whereas carbon dioxide absorption continues. So, global peatlands have a positive climate effect in the long run [148, 150, 157, 216–218].

Greenhouse gases flows from swamps are influenced by a wide range of interlinked physical, chemical and biological processes, the most important factor being the level of underground waters. Degradation of peatlands is a major cause of greenhouse gases emissions on the planet. When peatlands are drained, carbon and nitrogen are emitted as greenhouse gases into the atmosphere, nitrogen compounds enter surface waters. These emissions run on until the peatlands are dried up. Large amounts of methane come from drain ditches, water contains diluted organic carbon that is carried beyond the drained area and released as CO_2. 15% of the world swamps (0.4% of the planet earth, 65 million ha) have been drained and release about 1 150 Gt CO_2 annually. Total amount of emissions, including those caused by peat fires, make up 5% of the total CO_2 emissions of anthropogenic character. Moreover, drained peatlands cause other major environmental problems, namely the loss of natural biodiversity. Peatland emissions are usually augmented by deeper drainage and warmer climate. In all European countries where peatlands occupy more than 3% of agricultural lands, peatlands generate most (over 50%) greenhouse gases emissions associated with agricultural uses [148, 150, 157, 216–218].

Scandinavian and Baltic countries (Denmark, Greenland, Finland, Norway, Sweden, Estonia, Latvia, Lithuania) collectively possess nearly 250 000 km^2 of peatlands or 6% of their global area. Almost a half (45%) of peatland areas in Northern European and Baltic countries have been drained and annually release nearly 80Mt of carbon dioxide, i.e., 25% of the total CO_2 emissions of these countries. In Iceland and Latvia CO_2 emissions from peatlands are twice as large as the total emissions from other sources (without land use), in Estonia, Lithuania and Finland the peatland CO_2 emissions comprise 50%, in Sweden and Norway 25% and 15% respectively. Only in Denmark and Greenland peatland emissions make up less than 10% of the total CO_2 emissions [148, 150, 157, 216–218].

If the level of underground waters comes back to normal, greenhouse gases emissions become similar to those from undrained peatlands. It will take some time for reflooded peatlands to adapt to new conditions. During first years upon reflooding the greenhouse gases emissions are usually larger than those from untouched peatlands. Large methane emissions are observed. Climatic effect of methane is 23–28 times as high as that of CO_2, so reflooded peatlands will have “negative” effect on climate for minimum 100 years. Immediate beneficial effect of reflooded peatlands is that greenhouse gases emissions are lower as compared to the drained peatlands (by 6-28 t CO_2 per annum). It should be noted that reflooding can not be a determining factor for climate change mitigation [148, 150, 157, 216–218].

When swampy forests are cut on peatlands, the level of underground waters goes up thus leading to increased methane emissions and reduced carbon dioxide emissions. This negative climate effect is of short-term character. Changing level of underground waters can also affect carbon oxide emissions. The emissions are slowed down when the level of underground waters is stabilized [148, 218].

Clear-up of overgrown drainage ditches results in increased greenhouse gases emissions. Therefore, it is advisable to maintain high forest productivity on drained forested lands by means of the optimal level of underground waters. If the level goes down, CO_2 emissions from soil will increase and surpass its sequestration by the growing forests causing negative climate effect [148, 157, 218].

Some experts estimate that investments in measures to prevent degrading of peatlands or to restore degraded peatlands can be 100 times as cost-effective as other mitigation measures [148, 150, 157, 216–218].

7.2. Comparative analysis of greenhouse gases absorption by forests and swamps

Carbon accumulation by forest ecosystems varies depending in the geographical location, growth conditions and characteristics of stand components.

Research findings show that medium-aged coniferous stands absorb carbon at a very high rate (3.3–6.4 tC/year). It is slightly lower in young forests, mature coniferous and deciduous forests. Felling areas under reforestation absorb carbon to the varying amount of 0.1–0.7 tC/year. Data obtained from certain regions show that carbon absorption by forests of north-eastern China is estimated at 3.4 tC/ha per annum, in conservation forests of Mexico at 1.0 tC/ha per annum, in untouched rainforests of Asia (Brunei) it proves to be negative (–0,6 ± 6,1 t C/ha per annum). Application of mineral fertilizers (nitrogen and phosphorus) in pine forests growing on poor soils increase carbon absorption to 7.1 tC/ha per annum that is 50% higher than application of nitrogen fertilizers only (3.4 tC/ha per annum). In European part of Russia (temperate forests) average carbon absorption varied from 1.3 to 2.6 t/ha per annum [219–227].

Carbon absorption by swamp ecosystems is considerably lower than that of forest ones. Nowadays it ranges within 0.1–0.6 t/ha per annum. Sharply increased rates of carbon absorption (0.7–1.4 tC/ha per annum) were registered in various climatic periods. In the current (sub-Atlantic) climatic period the peat increment ranges from 0.1 to 0.9 mm/year with certain “peaks” of 1.8–2.6 mm/year [228–232, 134–138, 140, 253].

Thus, annual carbon absorption by forest ecosystems is usually 10 times as high as that by swamps. Mature, overmature forests and swampy felling sites under reforestation show minimal differences in carbon sequestration. Occasionally forests can act as carbon sources.

7.3. Conclusions

Measures on increasing the level of greenhouse gases absorption by forests and swamps based on best international practices include:

– Improved efficiency of forest management, including broader opportunities for decision-making by forestry enterprises and their organization units; gradual increase in logging operations by third parties, including all main types of fellings.

– Revision and upgrade of national forest policy and related regulations every 3–5 years based on new findings in the field of climate change mitigation by carbon sequestration and reduction of carbon emissions to adapt the existing approaches to sustainable forest management.

– Curricula and syllabi used in forestry education should be complemented by modules covering the issues of climate change mitigation and forestry adaptation.

– Review of the efficiency of new technology in terms of climate change (for instance, gene modification of tree species that are better adapted to future conditions, etc.).

– Conservation of the existing forests, including minimum removal of forested lands, creation of new forests on lands that are most suitable for forestry activities.

– More frequent cutting cycles, optimization of age structure, removal of stands of growth class IV and lower from forest utilization in order to maintain carbon sequestration features of forests.

– Adjustment of nature protection areas to achieve their optimal share in the national forest fund with regard to biodiversity conservation and carbon sequestration as well as socioeconomic aspects of the forest sector.

– Adaptation of approaches towards biodiversity conservation with account of future climate change (new species, alternative genotypes of plants).

– Optimization of tree species structure of forests with account of future climate change. Selection of tree species that are better adapted to draughts, formation of multistoreyed and mixed stands. Revision of the regions of seed origin for forest regeneration to select seeds adapted to future climate. Increased variety of tree species structure and total share of mixed planting (up to 50%) to improve resistance and reduce damage in spruce forests.

– More frequent partial final fellings through even gradual cuttings, group gradual cuttings, stage cuttings and selection cuttings with due encouragement measures: reduced quota of cutting operations to maintain the forest environment; financial penalties for violation of silvicultural requirements; support for preliminary forest regeneration, including special-purpose machinery; revision and improvement of organizational and technical aspects of cutting, etc.

– More frequent final clear cuttings with conservation of young growth (reduced amounts of young growth subject to conservation; motivation of forest users to carry out clear cuttings, stricter penalties for low-quality cutting) or gradual abolishment of clear cuttings without conservation of young growth.

– More frequent improvement fellings of lower intensity, selection of trees by classical silvicultural principles. Ensuring high density of stands and implementation of cuttings during winter or summer precipitation-free periods to improve resistance and reduce damage in spruce forests.

– Further implementation of ecologically sound cutting technology, specification of regulatory standards for leaving trees in the forest in order to conserve biological diversity, to create a new forest generation of complex structure when doing final clear cuttings.

– Increased stand growth can be achieved by application of mineral fertilizers, however, this measure bears certain risks such as expansion of pathogens, rapid development of mottled butt rot, reduced biodiversity, larger emissions of nitrogen oxide by forest soils and other indirect negative impacts. Thus, this measure cannot be recommended for wide use in the forest sector. Biological melioration can be a good alternative.

– Energy uses of wood (branches, stumps, firewood, etc.) assist to reduce greenhouse gases emissions due to substitution of fossil fuels, the best effect is achieved through substitution of coal. Logging residues should be harvested after needles and leaves have fallen off branches, 30-50% of the residues should be left in the forests depending on soil fertility. Data about the influence of stump extraction on carbon sequestration are controversial, therefore energy uses of stumps seem to be ineffective.

– Retention of carbon in long-life products and structures, replacement of energy-intensive materials (concrete, steel, etc.) that produce large amounts of greenhouse gases and reducing demand for fossil fuels. Support for wooden products that have added value and expansion of product lines based on research and innovations (new construction materials, biofuel, bioproducts such as antibiotics, bioactive paper, bioplastics, glues, biopesticides, herbal medicines, biochemical substances, industrial ferments, etc.), non-timber forest resources and recreational forest use, i.e., the development of bioeconomy.

– Planning, construction or modernization of wood processing facilities with regard to future tree species structure of forests.

– Plantation silviculture should be aimed at both maximum wood harvest and carbon sequestration. Bioenergy plantations are highly promising for mitigation of greenhouse gases emissions if they are created on non-forested lands of forest fund or other categories of lands.

– Legal ban on drainage of any swamp types; prevention of swamp degradation, restoration of degraded and reflooding of drained peatlands; restrictions and possible future ban on cuttings in swampy forests.

8

REVIEW OF THE NATIONAL LEGISLATION OF THE REPUBLIC OF BELARUS RELATED TO ABSORPTION OF CARBON DIOXIDE BY FORESTS

Carbon dioxide (CO_2) is the basic greenhouse gas in the Republic of Belarus and its share in the greenhouse gases emission is 64.4% in CO_2 equivalent (without CO_2 net-stock of "LULUCF" sector), dinitrogen monoxide (N_2O) – 18.4% and methane (CH_4) – 17,2%, HFC and SF_6 – 0,003%.

CO_2 emission caused by burning natural fuel is the basic source of greenhouse gas in the Republic of Belarus, where most greenhouse gas emission is produced in "Energetics" sector – 61.4% of total national emission. CO_2 emission has been reduced in the Republic of Belarus since 1990 caused by some structural changes in GDP.

Farming industry causes a powerful source of greenhouse gas of non-energy nature. This sector is the second one in greenhouse gas emission. It is 26.2% of total national greenhouse gas emission.

Basic causes of greenhouse gas emission in farming are organic and mineral fertilization, wastewater from fields and harvest waste, greenhouses, drained land cultivating. It produces N_2O, CO_2, CH_4.

The change in carbon content of forests and soils is taken into consideration when evaluating the CO_2 emission.

The global platform and relevant tools at international scale are necessary to fight effectively against greenhouse gas emission. In the Republic of Belarus the problem of greenhouse gas and CO_2 is mostly considered in the context of international conventions and contracts signed by the Republic of Belarus and its nationwide. In order to meet obligations on the contracts the Republic of Belarus includes CO_2 issues in domestic legislation.

8.1. Legal acts of the Republic of Belarus related to climate change and greenhouse gases

The vertically oriented hierarchical structure of normative legal acts has been created and functions in the Republic in Belarus which includes the influence on the climate. Legal acts of the Republic of Belarus are centralized in a single system by the agreement and identification of the legal acts hierarchy [233].

Normative legal act hierarchy in the Republic of Belarus:

– Constitution;
– Decrees and directives of the President;
– Laws;
– Government regulations;
– Normative legal acts of ministries and agencies;
– Normative legal acts created by local state jurisdiction;
– Local legal acts.

The Constitution of the Republic of Belarus has the highest judicial power. Laws, decrees, enactments and other acts of governmental agencies (government officials) are created in accordance with the Constitution. The right of citizens to a healthy environment is provided by the Constitution of the Republic of Belarus.

Normative legal acts of the President of the Republic of Belarus, unless otherwise provided by the Head of the State, are created as decrees and enactments which have binding force in the Republic of Belarus.

Decisions of the House of Representatives of the National Assembly of the Republic of Belarus are made as laws and acts. Acts of the House of Representative are focused on issues of administrative and controlling character.

Decisions of the Council of the Republic of the National Assembly of the Republic of Belarus are made as acts. Laws of the Republic of Belarus regulate the most important social relations. Effective laws of the Republic of Belarus are binding on a nationwide scale, unless otherwise provided by the law.

The Council of Ministers of the Republic of Belarus on the basis of the Constitution of the Republic of Belarus, acts of the President of the Republic of Belarus, laws of the Republic of Belarus adopts within its mandate normative legal acts as enactments which can’t be adopted by other national agencies of public administration.

Normative legal acts of the Council of Ministers of the Republic of Belarus on impact on the climate regulates the issues of the implementation of government policy, formulation and implementation of governmental programs in this field, proceeding the submission order, review and monitor climate projects, creation and maintenance of the National Register for Carbon Units.

Normative legal acts of Ministries and other national agencies of public administration can be adopted (passed) if only provided by the Constitution of the Republic of Belarus, normative legal acts of the President of the Republic of Belarus, laws of the Republic of Belarus, regulations for competent bodies and normative legal acts of the Council of Ministers of the Republic of Belarus. Normative legal acts of Ministries and other national bodies of public administration are adopted (passed) in the form of enactments and orders.

Local Deputies Councils, executive and regulatory bodies within their competence adopt normative legal acts in the form of decisions. Decisions of Local Deputies Councils regulate the issues of adoption and implementation of programs and measures to affect the climate locally, financial and administrative support, publicizing the information of impact of the climate.

"Law on Atmospheric Air" of the Republic of Belarus No.2-3 dated 16.12.2008 introduces legal and organizational basis of atmosphere air protection from pollution emission and is directed to maintain, restore the quality of atmosphere air and to ensure environmental safety. According to Clause 4 Article 2 of "Atmosphere Air Protection Law" of the Republic of Belarus No.2-3 dated 16.12.2008 the issues on climate effect of greenhouse gases are regulated by atmosphere air and environmental protection legislation.

A number of actions on reducing the greenhouse gases emissions were developed in the country over the five-year period (2011–2015). They are of long-term nature and are still applicable today. In particular, United Nation Framework Convention on Climate Change [235] and Kyoto Protocol [236] served as a basis for adoption of several important documents given below.

Resolution of the Council of Ministers of the Republic of Belarus No. 1155 dated 07.09.2012 "***On approval of the Strategy for greenhouse gases emissions reduction and absorption increase in the Republic of Belarus for 2007 – 2012***" [237]. A set of measures is provided in the document. They are aimed at emission reduction and greenhouse gases sink increase. The National Action Program for climate change mitigation for 2008-2012 was followed by the National Program for Climate Change Mitigation for 2013–2020. The Program was approved by the resolution of the Council of Ministers of the Republic of Belarus No.510 dated of 21.06.2013 [238]. It is aimed at greenhouse gases reduction by 8% in 2020 to the level in 1990 (for 2013–2020 years not less than 10 million t. in CO_2 equivalent). The total allocation of funds is about 10.205 million USD.

Resolution of the Council of Ministers of the Republic of Belarus No. 466 dated 14.04.2009 "***On Procedure for Submission, Review and Monitoring of the Projects on Voluntary Reduction of Greenhouse Gases Emissions***" made it possible to attract international investment in the projects on voluntary reduction of greenhouse gases emissions.

Presidential Decree of the Republic of Belarus No. 625 dated 08.12.2010 "***On several issues related to the reduction of greenhouse gases emissions***" strengthened a set of provisions enabling the economic entities to gain profit from the units of voluntary reduction of greenhouse gases emissions obtained from customers, including non-resident companies.

Presidential Decree of the Republic of Belarus No. 224 dated 07.05.2012 "On negotiations on draft amendments to Appendix B to the Kyoto Protocol of the UN Framework Convention on Climate Change" defines the stance of the Republic of Belarus on the amendment to Appendix B to the Kyoto Protocol of UN FCCC. The target of the Republic of Belarus for the second period of the Kyoto Protocol is to reduce greenhouse gases emissions by 20% in 2020 as compared to 1990 [239].

The Environmental Protection Strategy until 2025 approved by the decision of the collegium of the Ministry of Natural Resources and Environmental Protection of the Republic of Belarus No. 8-r dated of 28. 01. 2011. The Strategy defines measures to reduce impacts on the climate including the development of economic encouragement ways of economic agents to decrease greenhouse gases emission and provide the level of greenhouse gases emission not more than 110 million t by 2020.

By ***Presidential Decree of the Republic of Belarus No. 136 dated of 11.04.2011*** the Program of Economic and Social Development of the Republic of Belarus for 2011–2015 years was adopted. Payments improvement for greenhouse gases emission and creating the national system of greenhouse gases emission trading are aimed at preventing relevant ecological threats.

The most important tasks provided by the Decree are to reduce carbon fuel consumption, increase volume of compressed and liquefied gases use, use of diesel fuel with ultra-low sulfur content, Euro-4 and Euro-5 petrol. Economic encouragement of economic agents is coming up to develop low-waste technology and recycle secondary raw materials.

National Security Conception of the Republic of Belarus (Presidential Decree of the Republic of Belarus No. 575 dated of 09.11.2010) covers a lot of spheres which define national security including ecological safety. This document emphasizes the importance of creating an effective normative legal framework of ecological safety including payments system for natural resources consumption and adequate compensation for environmental damage.

Presidential Decree of the Republic of Belarus No. 244 dated of 13.06.2011 approved the implementation of the National Program for operating and development support of the National System for monitoring the environment in the Republic of Belarus for 2011–2015. It allows to receive data on atmosphere air condition in large and medium size cities in real-time mode and data on cross-border transfer of pollutants and greenhouse gases in surface air and stratosphere.

The Government Activity Program of the Republic of Belarus for 2011–2015, approved by the Resolution of the Council of Ministers of the Republic of Belarus No.216 dated of 18.02.2011**,** has a task to improve environment quality, attract investments in the frame of Kyoto Protocol, including emission trading. To implement the policy the government of the Republic of Belarus considers it necessary to introduce environmental insurance for creating a reserve source to cover expenses for environmental damage caused by technogenic and environmental accidents.

The National Program of Innovative Development of the Republic of Belarus for 2011–2015 was approved by the Resolution of the Council of Ministers of the Republic of Belarus No. 669 dated of 26.06.2011. It provides building biogas complexes of total electric capacity about 90 MW. In the sphere of using renewable sources and local types of fuel the hydroelectric power stations began operating, the boiler stations in mini-HPP were modernized by high technology. Total electric capacity was increased to 460 MW and other energy sources (garden waste, solar energy, household waste, petrol coke and others) to 863.5 thousand tons of reference fuel [240].

The Strategy for Technological Development of the Republic of Belarus until 2015 (Resolution of the Council of Ministers of the Republic of Belarus No. 1420 dated 01.10.2010) was adopted in order to create a competitive economy. Emissions of CO_2 and other greenhouse gases into the atmosphere reduced due to lower energy intensity of production, use of alternative fuels, efficient use of materials and renewable energy sources.

By order of the President of the Republic of Belarus ***the National Program for Sustainable Development*** has been developed and is being implemented. The Program integrates economic, social and environmental aspects where ecology is a goal-oriented component of economic development.

The Action Plan for More Intensive Development of Mineral and Raw Materials for 2016–2020 has been adopted by order of the President of the Republic of Belarus. The Plan provides for the reduction of environmental impacts. The system of handling municipal solid waste and secondary material resources of the Republic of Belarus makes it possible to extract and process nearly 16% of secondary raw materials.

The Union State Committee for Hydrometeorology and Monitoring of Environmental Pollution has adopted the Union State Program "***Development of the System of Hydrometeorological Safety of the Union State***" for 2017-2020.

Experts and scientists from Belarus and neighboring countries are carrying out extensive research into cross-border air pollution over large distances, wetlands protection and other important areas of nature protection.

8.2. International cooperation of the Republic of Belarus in the field of sustainable climate and international environmental conventions

International cooperation is fundamental to the policy of the Republic of Belarus in the field of climate change. Even more extensive cooperation in the field of climate change is maintained with such international organizations as United Nations Agency in Belarus, United Nations Program for Environment, United Nations Economic Commission for Europe, Organization for Economic Co-operation and Development, Intergovernmental Panel on Climate Change, World Meteorological Office, Organization for Security and Cooperation in Europe, CIS Interstate Council on Ecology.

The Strategy for Development of Hydrometeorological Activity of the CIS Member States was adopted on May 30, 2012 by the decision of the Heads of Government of the Commonwealth of Independent States (CIS).

The government of the Republic of Belarus is planning to implement measures aimed at stabilization of emissions and increased stock of greenhouse gases for the period of economic growth along with the measures to improve the quality of sinks and absorbents of greenhouse gases. Increasing of the level of carbon dioxide absorption by forest ecosystems is of vital importance for the Republic of Belarus where nearly 40% of the total country's area is covered by forests.

UN Framework Convention on Climate Change. Date and place of adoption: 09.05.1992, New York. The Republic of Belarus was among the first countries to sign the UN Framework Convention on Climate Change (UN FCCC). It was signed by Belarus on 14.06.1992, made effective on 09.08.2000.

At III Conference of the UN FCCC parties (Kyoto, December 1997) the Kyoto Protocol was adopted that specified quantity-related commitments to reduce greenhouse gases emissions in 2008–2012 for the countries listed in Appendix 1 to UN FCCC. These countries (individually or collectively) were committed to reduce the total greenhouse gases emissions by minimum 5% as compared to 1990.

By the Presidential Decree of the Republic of Belarus No. 370 dated 12.08.2005, the Republic of Belarus acceded to the Kyoto Protocol and UN FCCC. On 24.11.2005 Belarus became the full member of the Kyoto Protocol.

Being the party to the above mentioned international conventions, the Republic of Belarus should not exceed the specified amount of greenhouse gases emissions in 2008–2012. Within its domestic policy the country had to introduce strategic measures to stabilize emissions and increase absorption of greenhouse gases under the conditions of advancing economic development. At the same time it had to provide for further commitments to the Kyoto Protocol (2013–2017) when the allowed emissions were considerably reduced.

To solve the tasks mentioned ***the Strategy for Reduction of Emissions and Increasing of Absorption by Greenhouse Gases Sinks in the Republic of Belarus for 2007–2012*** was developed [237].

The Strategy aimed at determination of main lines of national actions that could ensure the specified mitigation of anthropogenic climate impacts, efficient development of economic sectors and satisfaction of people's demands through economically feasible and ecologically acceptable measures. The Strategy was developed in compliance with the action plan for implementation of the Kyoto Protocol to the UN Framework Convention on Climate Change for 2005–2012. The action plan was approved by the Resolution of the Council of Ministers of the Republic of Belarus No. 1582 dated 30.12.2005.

Basic documents for the development of the Strategy were:

• National Strategy for Sustainable Socioeconomic Development of the Republic of Belarus until 2020;

• Target Program for 25% of heat and power generation from local fuels and alternative energy sources until 2012;

• Conception of Energy Safety and Energy Independence of the Republic of Belarus and National Complex Program for Modernization of Main Production Facilities of Belarusian Energy System in 2006–2010;

• National Energy-Saving Program for 2006–2010;

• National Action Plan for Rational Utilization of Natural Resources and Environmental Protection for 2006–2010;

• Program of Socioeconomic Development of the Republic of Belarus for 2006–2010.

The Strategy widely uses terms and definitions of UN FCCC, the Kyoto Protocol and decisions of the UN FCCC Conference that specify requirements to national cadastres of anthropogenic emissions and absorption by greenhouse sinks.

In order to meet the commitments of the Republic of Belarus to the UN Framework Convention on Climate Change and the Kyoto Protocol the following documents were adopted:

– Presidential Decree of the Republic of Belarus No. 625 dated 08.12.2010 "***On several issues related to the reduction of greenhouse gases emissions***". The Decree regulates the issues of trading the units of greenhouse gases emissions reduction, agreements on the projects of voluntary reduction of greenhouse gases emissions, procedure of handling the funds received from trading the units of greenhouse gases emissions reduction [238];

– Presidential Decree of the Republic of Belarus No. 224 dated 07.05.2012 "***On negotiations on draft amendments to Appendix B to the Kyoto Protocol of the UN Framework Convention on Climate Change***";

– Resolution of the Council of Ministers of the Republic of Belarus No. 1582 dated 30.12.2005 "***On implementation of provisions of the Kyoto Protocol to the UN Framework Convention on Climate Change***" that approved the Action Plan for implementation of provisions of the Kyoto Protocol to the UN Framework Convention on Climate Change for 2005-2012;

– Resolution of the Council of Ministers of the Republic of Belarus No. 485 dated 10.04.2006 "***On approval of the Regulation of State Cadastre of anthropogenic emissions and absorption by greenhouse gases sinks***";

– Resolution of the Council of Ministers of the Republic of Belarus No. 585 dated 04.05.2006 "***On approval of the Regulation of National system for greenhouse gases inventory***".

– Resolution of the Council of Ministers of the Republic of Belarus No. 1077 dated 25.12.2006 "***On National Register of Carbon Units of the Republic of Belarus***";

– Resolution of the Council of Ministers of the Republic of Belarus No. 1144 dated 05.09.2006 "***On approval of the Regulation for Submission, Review and Monitoring of Joint Projects***";

– Resolution of the Council of Ministers of the Republic of Belarus No. 1145 dated 05.09.2006 "***On creation of the National Climate Change Board***";

– Resolution of the Council of Ministers of the Republic of Belarus No. 1117 dated 04.08.2008 "***On approval of the National Program for Climate Change Mitigation Measures for 2008–2012***";

Resolution of the Council of Ministers of the Republic of Belarus No. 466 dated 14.04.2009 "***On Procedure for Submission, Review and Monitoring of the Projects on Voluntary Reduction of Greenhouse Gases Emissions***";

– Resolution of the Council of Ministers of the Republic of Belarus No. 4 dated 22.01.2007 "***On Approval of the Instruction for Procedure of Creation and Maintenance of the National Register of Carbon Units of the Republic of Belarus***";

– Resolution of the Council of Ministers of the Republic of Belarus No. 10 dated 01.02.2007 "***On Measures to Implement the Resolution of the Council of Ministers of the Republic of Belarus No.1144 dated 05.09.2006***".

The ultimate goal of the Convention and all related legal documents is to achieve stabilization of greenhouse gases concentration in the atmosphere at the level that would prevent harmful anthropogenic climate impacts.

The following strategic documents have been adopted:

– National Strategy for Sustainable Socioeconomic Development of the Republic of Belarus until 2030 (adopted in 2015);

– State Program "Environmental Protection and Rational Utilization of Natural Resources" for 2016–2020 (adopted in 2016).

Data collection on CO_2 and other emissions polluting the atmospheric air is being carried out in terms of the effective legislation in Belarus [241, 242]. The Republic of Belarus has made several voluntary commitments for the second period of the Kyoto Protocol. They are related to the reduction of GDP energy consumption and greenhouse gases emissions with target values for 2015 and 2020 that are specified by basic program documents and legal regulations of the Republic of Belarus. The target values include:

• 8% reduction of greenhouse gases emissions as compared to 1990;

• greenhouse gases emissions of max. 110 million t by 2020;

• 29–32% reduction of energy consumption for 2011–2015 as compared to 2010.

Legal framework for climate impact regulation has been developed in the Republic of Belarus. Main legal regulations were adopted in 2005–2011 and are effective as of today. The number of the legal regulations is constantly growing. The total effect from the policy and measures amounted to 12.3 million t in CO_2 equivalent over the period from 2005 to 2014.

Paris Climate Agreement

The Paris Agreement is an agreement under the UN Framework Convention on Climate Change regulating measures on carbon dioxide reduction in the atmosphere from 2020. The Agreement was drawn up instead of the Kyoto Protocol in the course of the 21st Conference of the Parties to the UN Framework Convention on Climate Change

(December 08, 2015) and signed on April 22, 2016. The aim of the Agreement (according to Article 2) is to "enhance the implementation" of the UN Framework Convention on Climate Change, in particular, to keep a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius.

The Paris Agreement is a tool aimed at implementation of the resolution of the UN General Assembly "Transformation of Our World: Agenda of Sustainable Development until 2030". It also aims at maintaining the environmental integrity, support for renewable energy sources, "green" economy, transfer of high-effective technologies, climate change mitigation and adaptation.

In accordance with the Paris Agreement all countries including Belarus can have access to economic mechanisms encouraging measures on the reduction of greenhouse gases emissions and absorption of greenhouse gases by sinks. It also involves projects related to forests and measures on climate change adaptation of forestry and agriculture.

The Paris Agreement signed on April 22, 2016 was made effective on November 04, 2016.

By the Presidential Decree of the Republic of Belarus No. 345 dated 20.09.2016 the Republic of Belarus became a full party to the Paris Agreement [243]. The commitment of the Republic of Belarus is to reduce greenhouse gases emissions by 28% until 2030 as compared to 1990.

The outcomes of the First Session of the Conference of the Parties will provide the basis for the legal and regulatory framework until 2020 and onward. The legislation will be aiming at encouragement of greenhouse gases emissions reduction in the country, which includes application of the most advanced technology and financial support. Thereinafter the National Action Plan for Implementation of Commitments to the Paris Agreement will be developed.

Ramsar Convention on wetlands and their international importance primarily as wild birds habitats

Date and place of adoption: 02.02.1971, Ramsar, made effective in the Republic of Belarus on 10.09.1999 [244].

Convention on Wetlands (Ramsar, Iran, 1971) is an intergovernmental agreement that has a mission of "conservation and rational utilization of wetlands by means of national actions and international cooperation to achieve global sustainable development". The goal of the Ramsar Convention is conservation and rational utilization of wetlands as a means of global sustainable development.

Swamps are the lungs of our planet. They absorb carbon dioxide and release oxygen, form climate and maintain biological balance. It has been established that one hectare of natural swamps is able to absorb about one ton of greenhouse gases. In Belarus the per capita share of greenhouse gases is 6 t, in Germany – 11 t, in the USA – 25 t. Swamps have a great number of functions but it is non-disturbed "living" swamps that are able to fulfill their functions most effectively.

Swamps exercise another crucial role. They regulate the greenhouse gases content in the atmosphere, i.e. carbon dioxide (CO_2), methane (CH_4) and nitrogen oxide (N_2O). Swamps remove carbon dioxide from the atmosphere by means of peat formation, however, the peat formation ceases in disturbed swamps. In "dry" swamps the process of peat mineralization is triggered with peat decomposition and CO_2 emission into the environment. Therefore, drained swamps are a source of greenhouse gases. Stock and emission of greenhouse gases from degraded swamps should be taken into consideration to ensure more accurate evaluation of greenhouse gases emissions and to implement appropriate projects aimed at their reduction.

Putting swamps under the Ramsar Convention will result in both environmental and economic benefits, for instance, funds will be allocated to "restoration' projects [245].

Experts of the Institute of Earth Microbiology (Marburg, Germany) have developed a new method of CO_2 fixation by plants. It is based on a new ferment for carbon fixation that can theoretically accelerate the process in 2–3 times. Plants absorb CO_2 by the chemical process named Calvin cycle. It was established that the cycle was by 25% more effective than the Calvin cycle. If synthetic ferments are introduced into the living organism, the CETCH cycle will support natural photosynthesis. It is now hard to predict how efficient is the carbon cycle in real terms but the experts estimate it to be 2–3 times as fast as the Calvin cycle [246].

Another way of carbon dioxide absorption is location of "artificial trees" which has larger potential. They have a shape of giant fly swatters as high as 10 m and are quite commonly found along the roads, highways and in many polluted areas. Such trees capture CO_2 by a filter which is thousands of times as effective as real trees do. Afterwards the carbon dioxide is removed and sent to storage [247].

The Republic of Belarus is a country with unique nature and rich in wetlands. Therefore it plays a vital role in their conservation on European level. Our country is the only place in Europe with large areas of natural renewable wetlands which are able to intensively absorb carbon dioxide from the atmosphere. The age of wetlands in Belarus is nearly 1000 years. Nowadays their total area comprises 2.39 million ha, among them natural or near-natural swamps occupy 863 thousand ha, lakes – 10 thousand ha, rivers – 20.8 thousand ha.

The National Environmental Network has been created to conserve and protect wetlands which are natural CO_2 sinks. The scientific substantiation prepared by state scientific-production association "Scientific-Practical Centre for Bioresources of Belarus NAS". The Layout specified measures on the network development, formation and operation of its components which also include 25 local wetland reserves of the total area of 3600 ha. It is a system of geographical landscapes under special regimes of protection and utilization. The Network was created by the Law of the Republic of Belarus dated 20.10.1994 "***On Specially Protected Nature Areas***".

One of the key steps towards a real growth of the national "green" economy in the Republic of Belarus is the implementation of the **Project "Supporting the Transition to a Green Economy in the Republic of Belarus"** [248] funded by the European Union and implemented by the UN Development Program in several European countries. The development of ***ecosystem service*** market is recommended by the Project [248] as a promising trend of the "green" development of the national economy in Belarus. One of the key project objectives features carbon absorption services (preservation of the existing forest cover, forest plantations). The National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030 developed under this Task is compliant with and offers practical implementation of the Project "Supporting the Transition to a Green Economy in the Republic of Belarus" [248].

8.3. Current situation in the field of forests impacts on greenhouse gases and climate

National Action Plan on increasing the level of greenhouse gases absorption by sinks (forests, swamps)

Annually the vegetation of our planet captures 17- billion t of carbon and synthesizes about 400 billion t of organic substances. During formation of 1 t of absolutely dry wood 1.83 t of carbon dioxide is absorbed and 1.32 t of oxygen is released independent of tree species. It has been established that 1 hectare of 20-year-old pine forest has an average annual wood increment of 5 m^3 per1 ha, absorbs 9.35 t of CO_2 and releases 7.25 t O_2. Medium-aged stands are the most effective CO_2 sinks. One hectare of 60-year-old pine forest gives an average increment of 7.51 m^3 per 1 ha, absorbs 14.44 t CO_2 and releases 10.92 t O_2. Photosynthesis is even more intensive in 40-year-old oak forests with CO_2 absorption of 18 t per 1 ha and O_2 release of 13.98 t per 1 ha annually.

Studies have shown that in heavily gas-polluted areas poplar is the best absorbent. As a comparison, for five summer months a 25-year-old oak absorbs 28 kg of carbon dioxide, linden – 16 kg, pine – 10 kg, poplar – 44 kg. Little-leaved linden, ash, lilac and honeysuckle have good absorption capacity too [249].

The Republic of Belarus continues to provide significant ecosystem services at a global level, its forest cover being one of the largest in Europe (about 39% of the total area). The country also possesses large areas of undrained swamps (about 7% of the total area) that capture carbon dioxide and remove it from the atmosphere.

The national sector "Land-use, land-use change and forestry" is the only one where the level of carbon dioxide absorption surpasses the CO_2 emissions. In 2004 the surplus amounted to 11900.32 thousand t in CO_2 equivalent. Within the sector the emissions comprised 13010.90 thousand t, the stock amounted to 24911.22 thousand t in CO_2 equivalent.

The priority activities of the sector involve;

1. Measures on increasing of greenhouse gases stock:

– extension of forested areas due to reforestation of low-productive lands withdrawn from agricultural uses;

– restoration of floodplain oak forests;

– wider application of partial final fellings and conversion cuts of low-valuable forest stands;

– increasing of felling ages;

– recovery of disturbed swamps by reflooding with further peat formation and restoration of other natural sinks.

2. Measures on reduction of greenhouse gases emissions:

– improvement of technology, including technology of return of remaining plantations, technology of low till and vapor reduction;

– improved efficiency of wood uses [250].

CO_2 absorption by forests is one of relatively low-cost measures to eliminate climate change, for instance, by more effective forest management. Annually forests use over 25 million t of carbon dioxide for photosynthesis and other important life processes. Carbon sequestration capacity of forests has a considerable effect on total carbon balance of the atmosphere. Not all carbon dioxide absorbed by forest vegetation comes from the atmosphere. Soils, in particular forest soils are a major CO_2 source. Carbon is stored in dead wood, forest floor, roots. This carbon stock is especially valuable for low-disturbed forests. Clear cuttings, extensive forest fires disturb the carbon cycle. So, control of forest fires and diseases and conservation of biodiversity and forest sustainability contribute to carbon sequestration [251].

Essential CO_2 sinks are mosses, cyanobacteria and other unicell photosynthetic organisms. It has been found out that 7% of atmospheric carbon dioxide is absorbed by mosses, lichen and other unicell photosynthetic organisms.

7% of the absorbed CO_2 equals to nearly 14.3 billion t of CO_2 that is involved in the carbon cycle by mosses, cyanobacteria and lichen per one year. Therefore it is required to conserve swamps and forests of Europe as they are the most typical habitats of mosses and lichen. Moreover, these organisms capture from 30% to 80% of the total amount of biological nitrogen in the nitrogen cycle depending on the type of locality and climatic zone. By doing so, they maintain nitrogen balance and assist in conversion of carbon dioxide by vegetation since photosynthesis of trees, shrubs and grasses slows down when soils lack nitrogen [252].

The task of dilution of CO_2 and other greenhouse gases in the atmosphere cannot be solved by one economic sector of the country. For instance, ***State Program "Belarusian Forest" for 2016–2020*** has been developed to solve the tasks set by the President of the Republic of Belarus and the Government of the Republic of Belarus for the forest sector. The objectives of the Program include: increase of efficiency of forest, woodworking, furniture-making, pulp-and-paper and wood chemistry industries; implementation of up-to-date technologies; use of forest resources based on advanced practices of Finland and other countries with highly-developed forest sector and timber industry.

The aim of the State Program is to implement sustainable, cost-effective, ecologically responsible and socially-oriented management of forests, forest utilization, hunting and hunting grounds. Forests are natural reservoirs of CO_2 and are capable of retaining large amounts of carbon dioxide by absorbing it from the atmosphere. Therefore, increase of forested areas will contribute to CO_2 dilution in the air.

At the same time, the forest sector is regarded as an industry which can be most adversely affected by climate change. Hence, the ***Strategy for Adaptation of Forestry to Climate Change until 2050*** has been developed. Framework of a similar strategy for agriculture is being developed. In 2016-2019 legal regulations and organizational structure are to be prepared in order to implement specific measures on adaptation to climate change.

Recommendations for the Republic of Belarus

1. The legislation of the Republic of Belarus provides all necessary framework for forestry activities aimed at maintaining carbon sequestration capacity of forests and positive balance in the carbon dioxide "stock-emission" system. It also creates opportunities for increasing the absorption of carbon dioxide by the forest fund, carbon sequestration by the overground and underground phytomass and soil organic carbon of the forested lands.

2. Approval of the National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030 by the government of the Republic of Belarus will provide legal support for the actions on increasing the absorption of carbon dioxide by the forest fund, their planning, funding and control over the quality and scope of implementation by state forest management bodies and other forest owners.

3. Management of climate change aftereffects, forest conservation and contribution of forests to mitigation of adverse weather effects are global issues and should be addressed in the frame of close international cooperation, i.e.

- Raising of international funds to solve the above mentioned problems within the framework of international conventions and agreements adopted and signed by the Republic of Belarus.
- Involvement of stakeholders and agencies having similar tasks and goals in the international and interregional context.
- Organization of international/interregional conferences, workshops to identify common interregional/cross-border problems and to search for their solutions.
- Conclusion of interregional partnership agreements to establish cooperation in the field of solution search and exchange of experience.
- Preparation of interregional/international projects to achieve goals, solve tasks and implement recommendations resulting from the conferences and workshops held.

9

MEASURES OF THE NATIONAL ACTION PLAN ON INCREASING THE ABSORPTION OF CARBON DIOXIDE BY THE BELARUSIAN FOREST FUND

9.1. Strategy for increasing the absorption of carbon dioxide by the Belarusian forests

Below is the list of the most important program documents outlining the forestry policy in the field of mitigation of adverse weather and climate effects by means of carbon dioxide absorption by the forest fund of the Republic of Belarus:

- Presidential Decree of the Republic of Belarus No.345 dated 20.09.2016 “On adoption of international agreement”. (Accidence to the Paris Agreement of 22.04.2016).
- State Program for Climate Change Mitigation for 2013-2020. Approved by the Resolution of the Council of Ministers of the Republic of Belarus No.510 dated 21.06.2013.
- Strategy for Conservation and Sustainable Utilization of Biological Diversity. Approved by the Resolution of the Council of Ministers of the Republic of Belarus No. 1707 dated 19.11.2010 (as revised by the Resolution of the Council of Ministers of the Republic of Belarus No.743 dated 03.09.2015).
- National Action Plan for Development of “Green Economy” in the Republic of Belarus until 2020. Approved by the Resolution of the Council of Ministers of the Republic of Belarus No.1061 dated 21.12.2016.
- National Strategy for Sustainable Social and Economic Development of the Republic of Belarus until 2030. Approved by the record of the meeting of the Presidium of the Council of Ministers of the Republic of Belarus no.10 dated 02.05.2017.

▪ Strategic Plan for Forestry Development for 2015–2030. Approved by the Deputy Prime Minister of the Republic of Belarus M.I. Rusyj No.06/201-271 dated 23.12.2014.

▪ State Program "Belarusian Forest" for 2016-2020. Approved by the Resolution of the Council of Ministers of the Republic of Belarus No.215 dated 18.03.2016.

▪ Strategy of Adaptation of Agriculture of the Republic of Belarus to Climate Change (project) – CLIMAEAST EU Project, Minsk, 2017.

For the past 65 years the implementation of the provisions of these program documents has enabled carbon sequestration of 2 111 million t C by the forest fund of the Republic of Belarus and removal of 7 740 million t CO_2 from the atmosphere. Annual carbon dioxide absorption has increased 2.53 times and amounted to 46 986 thousand t in 2017, i.e., 42% of industrial greenhouse gases emissions was compensated.

Strategic areas of the forest sector for XXI century must involve the following measures and actions.

▪ **Change of forest management in swampy forests of transition and upland types.**

Swampy forests are tree stands growing on peat-boggy soils. They represent a unique ecological systems that are extremely rich in vegetation and biodiversity and an important element of CO_2 "stock-emission" balance. The pool of swampy forests contains about 60% of the total carbon amount in the forest fund phytomass. About 40% of carbon are retained by swampy forests as peat for long-term sequestration which is crucial to the issue of greenhouse gases.

If soil carbon is involved in the small biological cycle due to intensive peat mineralization under the conditions of forest drainage, forest cuts, soil cover damage by forestry machines, carbon dioxide can be released into the atmosphere in the amount of 2.68 t CO_2/ha/year.

Efficiency of the action. Enhanced biodiversity of forests, ecological services (tourism) continuous water protection and regulation function, prevention of carbon dioxide emission. Annual carbon dioxide absorption of +2.05 t CO_2/ha/year.

▪ **Improved effect from reforestation by application of advanced technology of planting stock cultivation and artificial forest regeneration methods.**

Annual carbon dioxide absorption of 3.30 t CO_2/ha/year can be achieved through reforestation after wood harvest by final felling by means of natural replacement of coniferous and deciduous forests by soft-wooded broadleaved ones (aspen, birch, grey alder) of vegetative origin, low commercial value and productivity.

Annual carbon dioxide absorption of 5.13 CO_2/ha/year can be achieved by forest plantation from ball-rooted nursery stock originated from high-quality selection seeds.

Efficiency of the action. Added annual carbon dioxide absorption of +1.83 t CO_2/ha/year.

▪ **Continuous environmental-protection function and conservation of natural components of forest ecosystem at the “felling – reforestation” stage**

Today final fellings are carried out over considerable areas of mixed coniferous-deciduous forests of natural origin, low-disturbed forests, differently-aged forests, forests with young growth, understorey, animal diversity and other components.

Methods of artificial or natural forest regeneration are used to restore typical forest landscape that has been exposed to anthropogenic impact as a result of clear cutting with the use of forestry and logging machinery. Natural reforestation is difficult to estimate under the present conditions and it seldom results in the complete restoration of the original natural landscape. Artificial forest ecosystems are more likely to lose genetic, species and landscape diversity and have degraded ecological functions. Annual carbon dioxide absorption will amount to 3.30 t CO_2/ha/year for natural reforestation and 5.13 t CO_2/ha/year for artificial reforestation.

Continuous environmental-protection function (density ≥ 0.6) and conservation of natural components of forest ecosystem at the “felling – reforestation” stage can be ensured through partial cuttings (gradual, voluntary-selective), ecologically sound logging technology, conservation of young growth, support for natural regeneration, care of naturally-regenerated forest. Cutting cycle is reduced by 5–7 years as compared to final felling. Annual carbon dioxide absorption amounts to 5.58 t CO_2/ha/year per a cutting cycle.

Efficiency of the action. Added annual carbon dioxide absorption of +0.45 t CO_2/ha/year as compared to final felling and forest plantations created by ball-root nursery stock. Added annual carbon dioxide absorption of +2.28 t CO_2/ha/year as compared to final felling and natural reforestation method.

▪ **Restoration of low-graded forest stands.**

Wood harvested during reconstruction is used for energy purposes and substitutes fossil fuels (coal, oil and natural gas). If average wood volume is 60 m^3 per 1 ha of the stand under restoration, the "emission" reduction (about 86 t CO_2 /ha) will be compensated by the same reduced amount of carbon dioxide absorption.

Forest plantations created upon the restoration give the average wood increment of 3.6 m^3/ha.

Efficiency of the action. Added annual carbon dioxide absorption of +5.13 t CO_2/ha/year due to the creation of normal stands in place of low-graded and low-productive ones.

▪ **Energy uses of wood harvested from littery forest.**

Experts estimate the current increment of Belarusian forests at 70 million m^3 per annum. About 10 million m^3 of this volume is not put into use and produces forest debris. The amount of debris is supplemented by windblown trees and stands as a result of more frequent adverse weather and climate catastrophic events. The wood harvested from the debris-strewn forests can be used for energy purposes replacing fossil fuels.

Efficiency of the action. Increasing of carbon dioxide absorption compensatory to its emission amounts to 1.4 t CO_2 /m^3 if wood harvested from debris-strewn forest is put to energy uses.

▪ **Energy uses of logging residues from final and other fellings.**

Uses of logging residues for energy purposes does not have any adverse environmental impact on biodiversity and soil fertility of forest ecosystem. Being secondary wood material used for energy purposes, logging residues replace fossil fuels (coal, oil and natural gas) and reduce greenhouse gases emissions.

Efficiency of the action. Increasing of carbon dioxide absorption compensatory to its emission amounts to 1.0 t CO_2 /m^3 if logging residues are put to energy uses.

▪ **Support for natural regeneration in ripening and mature stands.**

Carbon dioxide absorption can be increased by the formation of initial young growth of target tree species in the quantity of

≥4 thousand trees/ha with the height of ≥1.0 m and wood stock of ≥5 m^3/ha. This can also create necessary conditions for young forest to be formed by the year of the nest final felling.

Efficiency of the action. Increasing of carbon dioxide absorption to the amount of 7.2 t CO_2 per 1 hectare of the stand where support actions on natural regeneration have been taken.

▪ **Increasing of average density of stands.**

Efficiency of the action. Increasing of average density (P) of forested lands adds to annual carbon dioxide absorption in the amount of $\pm0{,}01P = \pm0{,}0674$ t CO_2/ha/year.

▪ **Long-term removal of certain forest tracts from forest management.**

The action involves conservation of carbon stock by certain forest tracts marked on the map and in the field to exempt them from forest cuts for 20–25 years (only sanitary and occasional improvement fellings are allowed).

Prospective areas for such projects are located in the zones of high-level radioactive contamination or areas of low allowable cuts with large amounts of commercially valuable ripening and medium-aged forests. In these areas exemption from final cuts will not be a radical action of forest management.

Efficiency of the action. The amount of annual carbon dioxide absorption is to be recorded. The action implies profit-making opportunities through trading of credits from carbon sequestration (carbon credits). Sustained (additional) annual absorption will amount to nearly 1.5–2.0 t CO_2/ha/year.

▪ **Forest growing on areas of unused, low-productive or low-fertile agricultural lands.**

The forest cover of the territory of Belarus comprised 39.8% as of 01.01.2017. At the same time, this cover is of nonuniform distribution by administrative districts (ranging from 10.1 to 65.5%), so necessary actions should be taken on sparsely forested lands.

The areas to be forested can include non-forested areas of the forest fund, small areas of unused and low-productive agricultural lands, low-fertile and agriculturally unprofitable lands.

Efficiency of the action. Creation of forested lands on the designated areas can ensure added annual carbon dioxide absorption of +4.0 t CO_2/ha/year.

▪ **Creation of spruce plantations under low-/medium-dense medium-aged birch and pine stands (understorey plantations) in the forest types series of bracken, myrtillus, wood-sorrel and Aegopodium.**

Understorey spruce plantations form the second storey by the time of final felling of the main storey of the stand. They yield wood stock of about 90–120 m^3/ha at the age of 40–50 years, their average density being 0.5–0.6.

Efficiency of the action. Added annual carbon dioxide absorption of +3.36 t CO_2/ha/year resulting from more extensive use of solar energy and soil fertility of the forest ecosystem.

9.2. Measures of the National Action Plan on Increasing the Absorption of Carbon Dioxide by the Belarusian Forest Fund until 2030

Measures of the National Action Plan are to be implemented within the framework of state programs of forestry development and within the limits of the allocated financial support as well as by raising extra-budgetary funds, international financial support, other legal sources. Tables 51–55 below outline measures and the scope of work to be implemented by forest management bodies, expected results of carbon dioxide absorption by the forest fund of the Republic of Belarus, etc.

Table 51

Measures to improve institutional environment by means of the National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030

Measures	Implementation period, years
1. Development of the sectoral program for increasing of average density of forests	2019
2. Entry of the following data into the Forest Cadastre: – total carbon amount of the forest fund; – phytomass carbon of the forest fund; – total dynamics of carbon sequestration by the forest fund.	2025

Measures	Implementation period, years
3. Entry of the following provision into the “Regulations of determination and approval of allowable final cuts in the forests of the Republic of Belarus”: – carbon weight sequestered by wood of the established allowable cut volume shall not exceed annual carbon absorption achieved by the planned targeted actions on increasing the carbon sequestration capacity of forests and non-forested lands of the forest fund.	2020
4. Supplementing forest management plans with the section “Measures on increasing the level of carbon dioxide absorption by forest fund”.	2025
5. Development of TCCP “Rules of calculation of greenhouse gases absorption and emission by forest fund components”.	2021–2023
6. Development of databank “Swampy forests of transition and raised types that are exploitable, unsuitable for logging, used for carbon sequestration”.	2019
7. Entry of the following provision into the Fellings Regulation of the Republic of Belarus: – final cuts are not allowed in swampy forests of transition and raised types used for carbon sequestration and biodiversity conservation.	2020

Table 52

Scope of work to implement measures of the National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030

No.	Measures	Governmental bodies and other agencies	Planned scope of works by periods	
			2018–2025	2026–2030
1.	Change of forest management regime in swampy forests of transition and raised types into nature protection regime. Exemption of certain forest type series (ledum, sphagnum, sedge-sphagnum and willow) from forest cuts will eventually ensure 10% compensation of CO_2 absorption by the forest fund due to increased carbon removal in harvested wood	Republic of Belarus	220.0	238.6
		Ministry of Forestry including:	220.0	238.6
		Brest SPFA	30.9	30.9
		Vitebsk SPFA	79.6	80.2
		Gomel SPFA	30.0	30.9
		Grodno SPFA	9.5	9.5
		Minsk SPFA	35.0	48.5
		Mogilev SPFA	35.0	38.6

2.	Creation of forest plantation by closed root nursery stock will ensure 2.8% compensation	Republic of Belarus	60420	52045
		Ministry of Forestry including:	59250	51350
		Brest SPFA	7650	9480
		Vitebsk SPFA	12750	9480
		Gomel SPFA	12750	9085
		Grodno SPFA	3800	3160
		Minsk SPFA	12100	10270
		Mogilev SPFA	10200	9875
		Department of Presidential Affairs of the Republic of Belarus	950	550
		Ministry of Education	25	25
		Belarus NAS	19	120
3.	Partial final cuts will ensure 3.2% compensation	Republic of Belarus	29760	41430
		Ministry of Forestry including:	27280	39500
		Brest SPFA	5600	6500
		Vitebsk SPFA	1040	8000
		Gomel SPFA	1040	7500
		Grodno SPFA	3600	3500
		Minsk SPFA	8800	7500
		Mogilev SPFA	7200	6500
		Department of Presidential Affairs of the Republic of Belarus	2000	1500
		Ministry of Defense	320	250
		Ministry of Education	80	90
		Belarus NAS	80	90
4.	Restoration of low-graded forest stands will ensure 2.5% compensation	Republic of Belarus	46.4	25.8
		Ministry of Forestry including:	42.3	22.4
		Brest SPFA	7.9	4.2
		Vitebsk SPFA	7.9	4.2
		Gomel SPFA	8.8	4.7
		Grodno SPFA	4.5	2.3
		Minsk SPFA	7.3	3.9
		Mogilev SPFA	5.9	3.1
		Department of Presidential Affairs of the Republic of Belarus	3.4	2.6
		Ministry of Defense	0.4	0.4
		Ministry of Education	0.1	0.1
		Belarus NAS	0.2	0.3

No.	Measures	Governmental bodies and other agencies	Planned scope of works by periods	
			2018–2025	2026–2030
5.	Energy uses of wood harvested from littery forest will ensure 20% compensation	Republic of Belarus	1770	1770
		Ministry of Forestry including:	1560	1560
		Brest SPFA	150	150
		Vitebsk SPFA	330	330
		Gomel SPFA	350	350
		Grodno SPFA	130	130
		Minsk SPFA	320	320
		Mogilev SPFA	280	280
		Department of Presidential Affairs of the Republic of Belarus	170	170
		Ministry of Defense	20	20
		Ministry of Education	10	10
		Belarus NAS	10	10
6.	Energy uses of logging residues from final and other felling sites will ensure 23% compensation	Republic of Belarus	1565	3975
		Ministry of Forestry including:	1380	3800
		Brest SPFA	150	500
		Vitebsk SPFA	300	700
		Gomel SPFA	300	700
		Grodno SPFA	120	400
		Minsk SPFA	260	800
		Mogilev SPFA	250	700
		Department of Presidential Affairs of the Republic of Belarus	140	140
		Ministry of Defense	30	20
		Ministry of Education	10	10
		Belarus NAS	5	5
7.	Support for natural regeneration in ripening and mature forests will ensure 2.5% compensation	Republic of Belarus	27840	26740
		Ministry of Forestry including:	26400	25700
		Brest SPFA	3200	3750
		Vitebsk SPFA	6000	4950
		Gomel SPFA	6000	4500
		Grodno SPFA	2000	4250
		Minsk SPFA	5200	4500

7.	Support for natural regeneration in ripening and mature forests will ensure 2.5% compensation	Mogilev SPFA	4000	3750
		Department of Presidential Affairs of the Republic of Belarus	1200	750
		Ministry of Defense	100	150
		Ministry of Education	70	70
		Belarus NAS	70	70
8.	Increase of average density of stands as compared to 2017 +0,016 (2025) and +0,044 (2030) will ensure 30% compensation	Republic of Belarus	+0.016	+0.044
		Ministry of Forestry including:	+0.016	+0.044
		Brest SPFA	+0.016	+0.044
		Vitebsk SPFA	+0.016	+0.044
		Gomel SPFA	+0.016	+0.044
		Grodno SPFA	+0.016	+0.044
		Minsk SPFA	+0.016	+0.044
		Mogilev SPFA	+0.016	+0.044
		Department of Presidential Affairs of the Republic of Belarus	+0.016	+0.044
		Ministry of Defense	+0.016	+0.044
		Ministry of Education	+0.016	+0.044
		Belarus NAS	+0.016	+0.044
		Republic of Belarus	+0.016	+0.044
9.	Long-term withdrawal of certain forest areas from forest management will ensure 9,2% compensation of CO_2 absorption by the forest fund due to increased carbon removal in harvested wood	Republic of Belarus	30.0	200.0
		Ministry of Forestry including:	30.0	200.0
		Brest SPFA	10.0	30.0
		Vitebsk SPFA	10.0	90.0
		Gomel SPFA	10.0	80.0

Forestry-related and other actions contained in Tables 51–54 enable the forest sector to maintain for the short-term the achieved, extremely high level of carbon "stock" in the forest ecosystem of Belarus, amounting to nearly forty-seven million ton carbon annually. The currently high level of annual carbon dioxide absorption can be attributed to the established age structure of forests with prevailing medium-aged stands that demonstrate maximum annual increment of carbon sequestration. Conservation of the carbon stock in the forests is also ensured by relatively low wood harvest (as compared to environmentally allowable wood harvest volumes) in the Belarusian forests due to the low share of mature stands and great emphasis of the forest conservation issues.

Table 53

Expected results of the implementation of measures of the National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030

Governmental bodies and other agencies	Added carbon dioxide absorption by period, thousand t CO_2		
	2018–2025	2026–2030	Total 2018–2030
Republic of Belarus	7900.9	16301.0	24201.9
Ministry of Forestry	7480.2	15101.3	22581.5
including:			
Brest SPFA	1091.6	2241.7	3333.3
Vitebsk SPFA	2077.0	3796.9	5873.9
Gomel SPFA	1337.9	3412.0	4749.9
Grodno SPFA	563.7	1257.7	1821.4
Minsk SPFA	1274.6	2436.2	3710.8
Mogilev SPFA	1135.4	1956.8	3092.2
Department of Presidential Affairs of the Republic of Belarus	302.4	854.4	1156.8
Ministry of Defense	35.0	102.2	137.2
Ministry of Education	13.0	36.3	49.3
Ministry of Emergencies	52.0	154.0	206.0
Belarus NAS	18.3	52.8	71.1

Table 54

Expected values of annual carbon dioxide absorption by means of the National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030, thousand t CO_2/year

Governmental bodies and other agencies	Years		
	2017	2025	2030
Republic of Belarus	46986	47012.9	47249.0
Ministry of Forestry	42585	42605.2	42630.3
including:			
Brest SPFA	5990	4111.6	5152.7
Vitebsk SPFA	8150	9604.0	6755.9
Gomel SPFA	8996	9966.9	11495.0
Grodno SPFA	5041	4145.7	3677.7
Minsk SPFA	7820	8057.6	8093.2
Mogilev SPFA	6588	6719.4	7455.8
Department of Presidential Affairs of the Republic of Belarus	2896	2872.4	3035.4
Ministry of Defense	348	324.0	212.2
Ministry of Education	154	156.0	179.3
Ministry of Emergencies	681	733.0	835.0
Republic of Belarus	238	238.3	272.8
Local executive bodies	84	84	84

The age structure dynamics is expected to change in the foreseeable future. Mature stands will be cut for both economic and environmental reasons. The mature stands have accumulated large carbon content over the years. However, their annual carbon dioxide absorption has a declining tendency and they become a source of carbon emission as they approach their biological age. This can be observed in old-aged forests of natural reserves and national parks.

The goal of maintaining the current level of annual carbon dioxide absorption by the forest fund can be achieved by increasing of forest productivity. For that matter the forestry-related measures proposed by the National Action Plan are very promising. They include creation of forest plantations by ball-rooted nursery stock with valuable selection properties, reconstruction of low-graded, reduction of cutting cycles of partial cuts to preserve young growth and to encourage natural reforestation. These actions are a mechanism of long-term effect for increasing of forest productivity. Highly promising are also diversified measures to increase the average density of stands. This issue was of little concern in the past; however, this can yield considerable wood stock increment due to improved reforestation and forest care measures.

Swampy forests occupy 18.6% of the total area and generate almost a half of the total carbon budget in the forest fund of Belarus. It is highly important to maintain and enhance the carbon sequestration capacity of swampy forests. Some of them are managed forests and their wood harvesting capacity can be increased as a result of intensive forest road construction. Mature upland forests are characterized by intensive wood increment, therefore it should be recommended to reduce wood harvest in swampy forests. The measures of the National Action Plan aiming at reinforcing of the conservation regime in the forests are advisable and highly effective in terms of carbon sequestration and improvement of forest biodiversity.

The forest sector implements a set of measures on optimization of the age and tree species structure of forests. These issues are addressed in the expert reviews contained in this report. The effects of the changes in age and tree species structure of Belarus on the level of carbon dioxide absorption have been assessed and demonstrate controversial results due to the existing balance of economic and ecological interests and not clearly identified climate and weather effects on the forest ecosystem of Belarus. Age structure of forests can be changed over long periods (many decades). The ideal age structure of forest, the so-called "normal" forest and associated sustainable forest management is characterized by the level of carbon dioxide absorption that is half as much as the current level. For this reason this report does not consider the optimization of the age structure of forests to be very promising. We also do not recommend changing the existing program for the optimization of the tree species structure of the Republic of Belarus. The change in the tree species of the Belarusian forests will not affect the level of carbon dioxide absorption due to the existing balance of economic and ecological interests.

These and other measures on increasing the level of carbon dioxide absorption by the forest fund require the improvement of the institutional environment of carbon sequestration (see Table 51 of this report).

The legislative framework regulating the issues related to carbon sequestration capacity of forests and their stabilizing effect on negative climate change impacts is regarded to be sufficient. We can refer to Presidential Decree No. 345 dated 20.09.2016 by which the Republic of Belarus committed to the Paris Agreement dated 22.04.2016 as well as to the State Program for Climate Change Mitigation for 2013–2030, etc.

Several regulations given in Table 51 should be developed within the forest sector. Among them we should mention monitoring of carbon flows through the National Forest Cadastre, recording of carbon sequestration when substantiating allowable cuts, more thorough approach towards carbon sequestration measures in the forest inventory projects. The existing guidelines on calculation of carbon dioxide absorption and emission by the forest fund of the Republic of Belarus should be updated and given the status of TCCP.

Table 52 describes suggested practical measures on increasing of carbon dioxide absorption by the forest fund together with the scope of work and implementation periods. As can be noted from the Table, about 94% of measures should be implemented by the Ministry of Forestry which is the main forest owner. However, other forest management bodies should also be involved in the suggested activities, their contribution becoming more essential in the future.

Table 55

Calculation of the increase in carbon dioxide absorption by the forest fund of the Republic of Belarus resulting from the targeted measures of the National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030

Targeted measures	Basic values	Calculation formula
1. Change of forest management regime in swampy forests of transition and boggy types	S_1: Area under targeted measure 1, [ha]. N_1: Duration of the record period of measure 1 under changed regime, [year]. F_1: Efficiency factor of targeted measure 1, [tCO_2/ha/year]. $F_1 = 2.05$ tCO_2/ha/year	$A_1 = 2.05\ S_1\ N_1$, where A_1 added carbon dioxide absorption through the change of swampy forests regime, [tCO_2]
2. Creation of forest plantation by closed root nursery stock	S_2: Area under targeted measure 2, [ha] N_2 Duration of the record period of measure 2 from the creation year of forest plantation, [year]. F_2: Efficiency factor of targeted measure 2, $F_2 = 1.83$ tCO_2/ha/year	$A_2 = 1.83\ S_2\ N_2$, where A_2 – additional carbon dioxide absorption through creation of forest plantation by ball-rooted nursery stock, [tCO_2]
3. Application of silvicultural system “partial cut – natural forest regeneration”	S_3: Area of single inventory of partial final cut after naturally regenerated forest has been transferred into the category of valuable forest stands, [ha]. N_3: Reduction of cutting cycle as compared to final cuts and artificial forest regeneration, [years]. F_3: Efficiency factor of targeted measure 3, $F_3 = 2.28$ tCO_2/ha/year	$A_3 = 2.28\ S_3\ N_3$, where A_3 – added carbon dioxide absorption through reduced cutting cycle of partial cuts with conservation of young growth and regeneration support measures , [tCO_2]
4. Restoration of low-graded forest stands	S_4: Area of the stands under restoration. Record of the area after the target has been achieved, [ha]. N_4: Projected period of the target achievement under measure 4 until the record year, [years]. F_4: Efficiency factor of targeted measure 4, $F_4 = 5.13$ tCO_2/ha/year	$A_4 = 5.13\ S_4\ N_4$, where A_4 – added carbon dioxide absorption through replacement of low-graded stand by more valuable one, [tCO_2]

5. Clearing-up of forest debris with subsequent energy uses of harvested wood	V_5: Volume of wood harvested from clearing-up of debris and used for energy purposes, [m^3]. F_5: Factor of atmospheric carbon dioxide absorption during formation of one unit of wood debris, $F_5 = 1.4\ tCO_2/m^3$	$A_5 = 1.4\ V_5$, where A_5 – volume of replacement of greenhouse gases “emission” by carbon dioxide absorption when fossil fuels are replaced by wood harvested from debris-strewn forest, [tCO_2]
6. Use of logging residues from final cuts for energy purposes	V_6: Volume of logging residues from final and other cuts used for energy purposes, [m^3]. F_6: Factor of atmospheric carbon dioxide absorption during formation of one unit of logging residues, $F_6 = 1.0\ tCO_2/m^3$	$A_6 = V_6$, where A_6 – volume of replacement of greenhouse gases “emission” by carbon dioxide absorption when fossil fuels are replaced by logging residues, [tCO_2]
7. Support of natural regeneration in ripening and mature forests	S_7: Area of ripening and mature forests under support measures for natural regeneration. Record of the area when young growth of targeted is available at ≥ 4 thousand trees/ha, height ≥ 1,0 m, wood stock ≥ 5 m^3/ha, [ha]. N_7: Duration of the period required for the formation of sufficient young growth by the year of final cut in the original stand, [year]. F_7: Efficiency factor of targeted measure 7, $F_7 = 7.2\ tCO_2/ha$	$A_7 = 7.2\ S_7 N_7$, where A_7 –level of increased carbon dioxide absorption by the forest stand with young growth, [tCO_2]
8. Increase of average density of stands	P_{cur}: One hundredth part of one density unit of forested lands of a forestry organization in the current year. P_{bas}: One hundredth part of one density unit of forested lands of a forestry organization in the basic year. N_8: Duration of the study period, [years]. $F_{0.01P}$: Change of annual carbon dioxide absorption by forested lands of the Republic of Belarus per one hundredth part of one density unit, $\pm 0.01P = \pm 0.0674\ tCO_2/ha$	$A_8 = 0.0377\ (P_{cur} – P_{bas})\ N_8$, where A_8 – level of carbon dioxide absorption resulting from measures on increasing the average density of forested lands of a forestry organization, [tCO_2]

9. Long-term withdrawal of certain forest areas from forestry management	S_9: Forest areas exempt from forest cuts for long-term period, [ha]. N_9: Period of exemption from forest cuts, [year]. F_9: Factor of the maintained annual carbon dioxide absorption resulting from the forest cut exemption under measure 9, $F_9 = (1.5–2.0)\ tCO_2/ha/year$. Factor F_9 is to be specifies depending on the conditions	$A_9 = (1.5–2.0)\ S_9\ N_9$, where A_9 – the maintained annual carbon dioxide absorption resulting from the forest cut exemption of certain forest tracts, [tCO_2]
10. Forest growing on unused, low-productive or low-fertile agricultural lands	S_{10}: Area of lands transferred for forest growing, [ha]. N_{10}: Duration of the period starting from afforestation year to the record year, [years]. F_{10}: Annual carbon dioxide absorption by tree stands on the areas under afforestation, $F_{10} = >4.0\ tCO_2/ha/year$. Factor K_{10} is to be specifies depending on the conditions	$A_{10} = >4\ S_{10}\ N_{10}$, where A_{10} – carbon dioxide absorption by tree stands on the areas under afforestation, [tCO_2]
11. Creation of spruce forests under the storey of medium-dense medium-aged birch and pine stands (understorey plantations)	S_{11}: Area of understorey spruce plantations, [ha]. N_{11}: Duration of the period starting from plantation year to the record year, [years]. F_{11}: Increased level of carbon dioxide absorption due to more extensive use of solar energy and soil fertility, $F_{11} = 3.36\ tCO_2/ha/year$	$A_{11} = 3.36\ S_{11}\ N_{11}$, where A_{11} – added carbon dioxide absorption by forest stands through the formation of the under storey spruce plantations, [tCO_2]

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Due to the estimated increase in wood harvest (Table 20), decreasing carbon stock and increasing carbon dioxide “emission” in the forest fund of the Republic of Belarus (Table 21), it is necessary to identify possible ways of compensation of the carbon dioxide “emission” estimated for 2018–2030, its amount being 23 912 thousand tCO2. Implementation of the measures suggested by the National Action Plan (Table 52) provides for additional carbon dioxide absorption by the forest fund to the amount of 24 019 thousand tCO2 that compensates for the estimated “emission” resulting from carbon removal due to wood harvest.

The compensation of the estimated carbon dioxide “emission” is ensured by the additional (excessive) absorption owing to the following measures: increased average density of stands – 30%; energy uses of logging residues from final and other cuts – 23%; energy uses of wood collected from debris clearing – 20%; change of management regime in swampy forests – 10%; long-term withdrawal of certain forest areas from forestry management – 9.2%; partial final cuts – 3.2%; creation of forest plantation by ball-rooted nursery stock – 2.8%; restoration of low-graded forest stands – 2.5% and support for natural regeneration in ripening and mature forests – 2.5% compensation for the estimated carbon dioxide “emission”.

Table 54 outlines the expected values of annual carbon dioxide absorption planned for public forest management bodies and other organizations (SPFAs) in accordance with the National Action Plan. To ensure reporting and recording procedures for the values given in Table 54, Table 55 provides guidelines for the calculation of increased level of carbon dioxide absorption resulting from the targeted measures to be implemented in the forest fund of the Republic of Belarus.

CONCLUSIONS AND RECOMMENDATIONS

1. Climate change of the recent decades has been caused by increased concentration of greenhouse gases in the atmosphere. Main greenhouse gases that have destabilizing effect on the atmosphere are carbon dioxide, methane, nitrogen oxide and chlorofluorocarbons. The total amount of greenhouse gases is dominated by carbon dioxide (76%). Absorption of substances by forest vegetation occurs during nutrition process. The nutrition can be divided into carbon or aerial, plant nutrition (photosynthesis), water nutrition (hydrogen and oxygen), nitrogenous and mineral. Plants take up nitrogen through their roots in the form of mineralized ammonia nitrogen. Specific weight of absorption of nitrogen oxide by plants is inconsiderable as compared to nitrogen fixation of atmospheric molecular nitrogen. Thereby forests have no significant impact on mitigation of the greenhouse effect. Main biological sink of atmospheric methane is its oxidation in soil. Methane absorption by forest fund is relatively small, i.e., about 0.5 million t in CO_2 equivalent. Natural absorption of chlorofluorocarbons by Belarusian forests is lower than 4 t per year. The role of forest and other vegetation communities of the forest fund as greenhouse gases sinks is exercised through carbon dioxide absorption during primary synthesis of organic substances (photosynthesis). In view of this, the National Action Plan for greenhouse gases in forests and swamps developed under this task involves measures on increasing the absorption of carbon dioxide as the most prevailing greenhouse gas on all forest fund lands of the Republic of Belarus.

2. Basic assumptions have been made for balance calculations of carbon flows in forests that are commonly applied by IPPC methodology. The study analyzes methodical approaches towards carbon budget record in Russian forests (FCA), Center of Forest Ecology and Productivity of the Russian Academy of Sciences (CFEP). The CBM-CFS model of carbon budget calculation applied by Canada’s National Forest Carbon Monitoring, Accounting and Reporting System is considered. EFIMOD-2 computer simulation system developed by the Institute of Physical-Chemical and Biological Problems of Soil Science (Russia) and European Forest Institute

(Finland) is described. The report contains the review of the Russian mathematical simulation model FORRUS-S, Information System of Identification and Mapping of Carbon Sequestration by Forests (V.A. Usoltsev),etc. Conclusions have been made as to applicability of “Methodology of evaluation of annual CO_2 ‘sink-emission’ flows and total carbon sequestration by Belarusian forests” approved by the Ministry of Forestry of the Republic of Belarus [6]. The report gives substantiation of key indicators of the Belarusian methodology for the evaluation of carbon dioxide absorption by forests and techniques of carbon flows data collection and processing in forests. It has been assessed how “Forest Resources” GIS and “Forest Resources” Mapping and Taxation Databank can be applied to evaluate carbon stock in forests and other forest fund components. Summary statement and conclusions have been made for the recoding of carbon dioxide absorption in the forest fund of the Republic of Belarus. Application of the methodology [6] provides rather high accuracy of calculation of carbon sequestration by Belarusian forests which is ensured by regularly updated subcompartment and cartographic databank “Forest Resources” GIS. Therefore the methodology [6] can be updated to a higher-status regulation, i.e., TCCP “Calculation rules for absorption and emission of greenhouse gases by the forest fund components”. This measure is contained in the National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030. Calculations of greenhouse gases in the forest fund [6] are made only for carbon dioxide due to the fact that absorption/emission of other greenhouse gases such as nitrogen oxide, methane, fluorophtorocarbons are very insignificant.

3. When recording greenhouse gases emissions and absorption by forest ecosystems the most unbiased information can be obtained from direct measuring of CO_2 flows between the atmosphere and forest ecosystem. Such measurements are to be made by micrometeorological eddy covariance method along the vertical profile “ecosystem – atmosphere”. This method involves costly equipment, large scope of field studies whereas the obtained carbon cycles results will be time- and space-constrained and leave out the possibility to determine the carbon cycle balance between the forest ecosystem and atmosphere integrally. All other approaches towards the calculation of carbon cycles in forests are derived from the IPCC methodology, namely FCA

(Russian Federation), REFCB (Russian Academy of Sciences), CBM-CFS (Canada), European Forest Institute (Finland), etc. Basic methodological framework for the calculation of carbon accumulation and carbon dioxide absorption in the forest fund of Belarus is the methodology of Intergovernmental Panel on Climate Change (IPPC). Based on the principles of IPPC methodology it is required to develop a legal regulatory document for the calculation of carbon flows in the forest fund of Belarus [6]. Application of the methodology [6] provides rather high accuracy of calculation of carbon sequestration by Belarusian forests (Tables 1–6) which is ensured by regularly updated subcompartment and cartographic databank "Forest Resources" GIS. Therefore the methodology [6] can be updated to a higher-status regulation, i.e., TCCP "Calculation rules for absorption and emission of greenhouse gases by the forest fund components.". This measure is contained in the National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030 (Table 45). Calculations of greenhouse gases in the forest fund [6] are made only for carbon dioxide due to the fact that absorption/emission of other greenhouse gases such as nitrogen oxide, methane, fluorophtorocarbons are very insignificant. When developing the TCCP, the following provisions and conclusions of the best international methodologies should be taken into consideration:

- Integrated subcompartment and cartographic databank of GIS "Forest Resources" makes it possible to calculate greenhouse gases absorption on any forested area and by any methodology that is using the GIS data. The integrated geoinformation system has an only drawback of incomplete consistency of subcompartment and cartographic databanks upon a certain period of time after basic forest inventory.
- Availability of electronic cartographic databanks covering the whole forest fund makes it necessary to create a software package for ongoing update of the forest fund data by entering the changes into both taxation and cartographic databanks by legal entities of the forest sector with subsequent data transfer to central server.
- To ensure more complete record-keeping of the carbon dioxide absorption by forest fund areas it is required to improve methods for the assessment of greenhouse gases absorption by non-forested lands, open forest plantations and certain types of non-forested lands (swamps, agricultural lands, etc.) as well as by woody-shrub areas

outside the forest fund and occupying about 1 million ha as per forest cadastre data.

- To estimate the current average annual greenhouse gases absorption forest monitoring data can be used more widely, i.e., data from the stationary monitoring stations located on the transnational network (16×16 km) and covering the whole forest fund area of the country.

4. Although extensive research has been carried out into the carbon sequestration by forests and the climate effect of carbon, many issues have not been given sufficient attention. They involve the determination of carbon stock and increment in Belarusian forest stands across age classes and carbon accumulation prospects.

- Total carbon amount sequestered by pine stands is 230.5 million t. The largest carbon accumulation is observed in age class 3 (65.3 million t), 4 (97.2 million t) and 5 (43.2 million t). Young forests accumulate much lower amounts of carbon due to their small wood stock per 1 ha and relatively small areas, i.e., age class 1 – 2.9 million t, age class 2 – 11.8 million t. From age class 6 and onward the carbon sequestration declines sharply due to the small areas occupied by the pine stands of older age. The reduction of the old-aged pine stands results in the fact that the average change of the carbon content in stemwood of a growing stand starts to decrease at age class 5 and onward. Average current annual change of carbon stock remains relatively steady (15 thousand t). The increase of allowable cuts will cause the reduction of old-aged stands and annual carbon sequestration by stemwood.
- Annual current carbon increment across age classes involves the carbon contained in dead wood amounting to 8 million t or 4% of the stemwood carbon. As of 01.01.2031, the carbon stock in pine stands will remain relatively steady. The decrease of total carbon amount is rather inconsiderable (only 2%). This can be explained by the fact that main carbon sinks (age classes 3, 4 and 5) occupy large areas and the allowable cuts are not to be considerably changed until 2030. As of 01.01.2031, the average change of carbon stock per 1 ha remains almost unchangeable, i.e., from 15.4 to 21.4 thousand t. From 2030 and onward the carbon stock dynamics will be more critical due to increased allowable cuts and decreased areas of age classes 3, 4 and 5.
- The present age structure of pine stands does not conform to the theory of normal forest, as we can observe huge lack of young growth

and certain shortage of mature stands whereas the medium-aged forests are the predominant ones. However, the optimal distribution of stands by age classes according to the theory of normal forest will not ensure maximum level of carbon absorption as the felling ages of large- and medium-sized commercial timber are established by technical maturity and cannot provide for the opportunity to achieve the maximum wood stock throughout the whole life of forest stands.

- Maximum level of carbon dioxide absorption by pine stands can be achieved if felling ages are established by ecological maturity of forests. The ecological maturity is determined by maximum average carbon increment throughout the whole life of forest stands.
- The ecological maturity of pine stands occurs in age class 6, i.e., 101–120 years. With respect to the ecological maturity of forest and the theory of normal forest, the optimal distribution of stands by age classes looks as follows: age class 1 – 18 %, 2 – 17%, 3 – 17 %, 4 – 16 %, 5 – 16 %, age class 6– 16 %. The optimal age structure of pine stands can be achieved not sooner than the 2050s-2060s. To ensure the optimal age structure, it is necessary to restrict the allowable cuts between 2031 and 2050. The present medium-aged ripening stands will become mature by that time, so their clear cutting will dramatically reduce further forest uses which is contradictory to the theory of normal forest.
- To increase the carbon sequestration by pine stands and to optimize their age structure, the following measures can be recommended:

– establishing pine formations on the felling areas of former birch forests. Until 2031we can expect about 500 thousand ha of birch stands to be cut (230 thousand ha of mature stands and nearly 200 thousand ha of ripening stands that are to become mature in 10 years). Pine plantations can be created on about a half of the areas taking up 10-15 thousand ha per annum;

– restoration of low-value birch stands. The total restoration reserve can make up 10-15 thousand ha. Taking into account the fact that this activity proves to be rather costly, the factual restoration area will obviously comprise 3-5 thousand ha;

– establishing pine plantations on non-forested lands. This reserve is not very ample, however it can amount to 3 thousand ha per annum;

– regulation of allowable cuts in pine forests in order to reduce it in 2040–2060 to optimize the age structure. This being the case, the allowable cuts for age class 6 will remain more or less the same, according to the theory of normal forest, the optimal distribution of stands must involve 18% of mature stands of age class 5 and 16% of age class 6. The minor decrease in mature forests must be compensated by additional increment over 20 years.

- All the measures listed above involve considerable expenses and long time of implementation. Thus, the age structure of stands can be optimized not earlier than 2050–2060. The measures must be contained in a special program with appropriate time scheduling and allocation to forestry establishments. This can be done during forest inventory when developing forest inventory plans.
- Forests of Belarus are a major natural renewable economic asset of the country. Belarus has to maximize the forest cuts in order to ensure ongoing supply of timber and wooden products to domestic and external markets. Maximization of carbon sequestration by Belarusian forests can only be achieved through reduced forests uses. Thus, the measures on increasing the carbon sequestration must be accompanied by international compensation (through CO_2 quotas) for the economic losses resulting from the reduced timber volumes brought to the markets. Only under these conditions it will be feasible to maximize the carbon sequestration by Belarusian forests.

5. Optimization of the tree species structure in the forests of Belarus can be an efficient tool of increasing the level of carbon dioxide absorption if ecological-economic factors are taken into consideration in the process of forest management. They include:

– the choice of trees for improvement felling should be based upon the biological features of tree species in terms of their carbon sequestration efficiency;

– evaluation of carbon sequestration efficiency of stands should take into account the wood stock per 1 ha and clear-cut age;

– optimization of tree species structure of Belarusian forests [9] will lead to their improved carbon sequestration efficiency;

– carbon sequestration effect from the optimization of tree species structure can be maximized by re-establishing the clear-cut age for coniferous and hard-leaved stands at 100 years for forest group I, for soft-wooded broadleaved at 50 years;

– due to global climate change impacts, in particular in the southern regions of Belarus [5], and adverse weather effects of 2016 it is recommended to do extensive environmental and biological studies in order to develop measures on increasing forest sustainability on the affected areas;

– in order to improve the efficiency of tree structure optimization it is advisable to develop a software package based on GIS "Forest Resources" that can be used to estimate carbon sequestration efficiency of planned forest plantations;

– the extent of tree species optimization (replacement of pine by birch) should be revised as it is set too high;

– the share of pine stands (50.6% in 2017) should be increased by 1% until 2030 by means of reducing the share of birch stands (22,7% in 2017).

6. Comparative analysis of the level of carbon dioxide absorption by forests and swamps proves that carbon accumulation by forest ecosystems varies depending on their geographical location, growth conditions and characteristics of individual stand components.

▪ Studies show that highly intensive carbon absorption is observed in medium-aged coniferous stands (3.3–6.4 t C/ha per annum). It is less intensive in young forests, mature coniferous and deciduous stands and ranges from 0.1 to 0.7 t C/ha per annum in forests under after-cut restoration. Data for several regions show that average carbon accumulation in forests of north-east China ranged from 1.9 to 3.4 t C/ha/year, in conservation forests of Mexico 1.0 t C/ha/year and was registered as negative in untouched forests of Asia (Brunei), i.e., –0,6 ± 6,1 t C/ha/year. Application of mineral fertilizers (nitrogen and phosphorus) in pine stands increases carbon sequestration as much as 5.1 t C/ha/year which is by 50% higher than application of nitrogen fertilizers only (3.4 t C/ha/year). In the European part of Russia the average carbon accumulation ranged from 1.3 to 2.6 t C/ha/year.

▪ Carbon absorption by swamp ecosystems is considerably lower than that of forest ones. Nowadays it ranges within 0.1–0.6 t/ha per annum. Sharply increased rates of carbon absorption (0.7–1.4 tC/ha per annum) were registered in various climatic periods. In the current (sub-Atlantic) climatic period the peat increment ranges from 0.1 to 0.9 mm/year with certain "peaks" of 1.8–2.6 mm/year. Thus, annual carbon absorption by forest ecosystems is usually 10 times as high as that by swamps. Mature, overmature forests and swampy felling sites under reforestation show minimal differences in carbon sequestration. Occasionally forests can act as carbon sources.

7. Measures on increasing the level of greenhouse gases absorption by forests and swamps include the following actions.

- Improved efficiency of forest management, including broader opportunities for decision-making by forestry enterprises and their organization units; gradual increase in logging operations by third parties, including all main types of fellings.
- Revision and upgrade of national forest policy and related regulations every 3–5 years based on new findings in the field of climate change mitigation by carbon sequestration and reduction of carbon emissions to adapt the existing approaches to sustainable forest management.
- Curricula and syllabi used in forestry education should be complemented by modules covering the issues of climate change mitigation and forestry adaptation.
- Review of the efficiency of new technology in terms of climate change (for instance, gene modification of tree species that are better adapted to future conditions, etc.).
- Conservation of the existing forests, including minimum removal of forested lands, creation of new forests on lands that are most suitable for forestry activities.
- More frequent cutting cycles, optimization of age structure, removal of stands of growth class IV and lower from forest utilization in order to maintain carbon sequestration features of forests.
- Adjustment of nature protection areas to achieve their optimal share in the national forest fund with regard to biodiversity conservation and carbon sequestration as well as socioeconomic aspects of the forest sector.
- Adaptation of approaches towards biodiversity conservation with account of future climate change (new species, alternative genotypes of plants).
- Optimization of tree species structure of forests with account of future climate change. Selection of tree species that are better adapted to draughts, formation of multistoreyed and mixed stands. Revision of the regions of seed origin for forest regeneration to select seeds adapted to future climate. Increased variety of tree species structure and total share of mixed planting (up to 50%) to improve resistance and reduce damage in spruce forests.
- More frequent partial final fellings through even gradual cuttings, group gradual cuttings, stage cuttings and selection cuttings with due encouragement measures: reduced quota of cutting operations

to maintain the forest environment; financial penalties for violation of silvicultural requirements; support for preliminary forest regeneration, including special-purpose machinery; revision and improvement of organizational and technical aspects of cutting, etc.

- More frequent final clear cuttings with conservation of young growth (reduced rates of young growth to be conserved; motivation of forest users to carry out clear cuttings, stricter penalties for low-quality cutting) or gradual abolishment of clear cuttings without conservation of young growth.
- More frequent improvement fellings of lower intensity, selection of trees by classical silvicultural principles. Ensuring high density of stands and implementation of cuttings during winter or summer precipitation-free periods to improve resistance and reduce damage in spruce forests.
- Further implementation of ecologically sound cutting technology, specification of regulatory standards for leaving trees in the forest in order to conserve biological diversity, to create a new forest generation of complex structure when doing final clear cuttings.
- Increased stand growth can be achieved by application of mineral fertilizers, however, this measure bears certain risks such as expansion of pathogens, rapid development of mottled butt rot, reduced biodiversity, larger emissions of nitrogen oxide by forest soils and other indirect negative impacts. Thus, this measure cannot be recommended for wide use in the forest sector. Biological melioration can be a good alternative.
- Energy uses of wood (branches, stumps, firewood, etc.) assist to reduce greenhouse gases emissions due to substitution of fossil fuels, the best effect is achieved through substitution of coal. Logging residues should be harvested after needles and leaves have fallen off branches, 30-50% of the residues should be left in the forests depending on soil fertility. Data about the influence of stump extraction on carbon sequestration are controversial, therefore energy uses of stumps seem to be ineffective.
- Retention of carbon in long-life products and structures, replacement of energy-intensive materials (concrete, steel, etc.) that produce large amounts of greenhouse gases and reducing demand for fossil fuels. Support for wooden products that have added value and expansion of product lines based on research and innovations (new construction materials, biofuel, bioproducts such as antibiotics,

bioactive paper, bioplastics, glues, biopesticides, herbal medicines, biochemical substances, industrial ferments, etc.), non-timber forest resources and recreational forest use, i.e., the development of bioeconomy.

- Planning, construction or modernization of wood processing facilities with regard to future tree species structure of forests.
- Plantation silviculture should be aimed at both maximum wood harvest and carbon sequestration. Bioenergy plantations are highly promising for mitigation of greenhouse gases emissions if they are created on non-forested lands of forest fund or other categories of lands.
- Legal ban on drainage of any swamp types; prevention of swamp degradation, restoration of degraded and reflooding of drained peatlands; restrictions and possible future ban on cuttings in swampy forests.

8. The review of national legislation of the Republic of Belarus related to greenhouse gases absorption by forest and swamps and commitments to international conventions and agreements leads to the following conclusions and recommendations:

- All legislative measures in the Republic of Belarus are developed and implemented within the framework of the existing international agreements.
- Scientific and technological research and development is largely based on the international projects and agreements.
- Belarus possesses large potential for implementing the international policy on CO_2 emissions reduction.
- Measures to reduce CO_2 emissions can be implemented in several ways:

– switch to energy-saving technology and alternative sources of fuel;

– increasing of forest stands areas and sustainable forest management;

– conservation and rational utilization of the available wetlands.

The legislation of the Republic of Belarus provides all necessary framework for forestry activities aimed at maintaining carbon sequestration capacity of forests and positive balance in the carbon dioxide “stock-emission” system. It also creates opportunities for increasing the absorption of carbon dioxide by the forest fund, carbon sequestration by the overground and underground phytomass and soil organic carbon of the forested lands. Approval of the National Action

Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030 by the government of the Republic of Belarus will provide legal support for the actions on increasing the absorption of carbon dioxide by the forest fund, their planning, funding and control over the quality and scope of implementation by state forest management bodies and other forest owners. Management of climate change aftereffects, forest conservation and contribution of forests to mitigation of adverse weather effects are global issues and should be addressed in the frame of close international cooperation, i.e.:

- Raising of international funds to address the within-named problems in the frame of international conventions and agreements signed by the Republic of Belarus.
- Involvement of stakeholders and agencies having similar tasks and goals in the international and interregional context.
- Organization of international/interregional conferences, workshops to identify common interregional/cross-border problems and to search for their solutions.
- Conclusion of interregional partnership agreements to establish cooperation in the field of solution search and exchange of experience.
- Preparation of interregional/international projects to achieve goals, solve tasks and implement recommendations resulting from the conferences and workshops held.

9. Dynamic development of the forest ecosystem in Belarus has a sustainable tendency for increasing forest productivity and wood stock. Over the period from 1945 to 2017 the total forest fund area has increased in 1.55 times (+3406.8 thousand ha), productivity (average wood stock) in 3.1 times (+125 cubic metres per 1 ha), total wood stock in 5.5 times (+1451.3 million cubic metres). This was made possible through effective forestry operations of forest regeneration and forest growing, measures on increasing productivity and improving forest care, rational forest utilization, etc. Increase of wood stock and phytomass of the forest ecosystem respectively leads to enhanced carbon net flow from the atmosphere to forest with its subsequent absorption. Since 1956 (first post-war forest inventory) the carbon content has increased in the forest fund. As of 01.01.2017 the carbon pool of the forest fund of the Republic of Belarus comprised 3492.7 million ton. The increase of the forest fund area (1956–2017) in 1.3 times resulted in the subsequent increase of carbon pool in

2.52 times. The carbon increment is almost twice as much as the forest fund increment. This resulted from a number of factors.

First, we should mention a key permanent factor of measures to enhance forest productivity as the main strategic goal of the forest sector. This also improves the carbon sequestration capacity of forests. Conventional and new forestry operations are in place on the condition that they enhance forest productivity. The list of the actions is very long due to their diverse range and ongoing use in forestry. Further we will focus on the efficiency of certain measures taken in forestry. There was a monitoring of long-term (nearly 60 years) effect from the forestry measures on wood stock increment and annual carbon sequestration by the stands in Ivye experimental production forest district and Negoreloe experimental forestry district. During the monitoring a considerable increase of carbon sequestration capacity was registered. By methods of forest regeneration after final fellings the increase of carbon sequestration was established as follows: forest plantations – +140 tC/year, natural reforestation with assistance measures – +0.99 tC/year. Increase resulting from forest care activities comprised: restoration with subsequent forest plantation – +1.39 tC/year, improvement fellings – +1.18 tC/year.

Second, a current factor of great impact on carbon sequestration is the present age structure of forest and wood harvest volumes. The current age structure of forests is not the optimal one but is very conducive to wood increment and associated carbon sequestration. The present index of age structure of national forests is equal to 0.30; the optimal age structure has an index set to zero. Today medium-aged stands occupy 44.3% of the forested areas and are by 14.3% higher than the optimal share. Medium-aged stands are characterized by maximum current wood increment that favours current increase of carbon pool in Belarusian forests.

Third, the forest sector of Belarus experienced an extension of areas of forest group I accompanied by restricted wood harvest for the past three-four decades. At the same time, the share of commercial forests of group II was decreasing (1983 – 64%, 2015– 45.1%). Thus, as the total forest area was increasing over the period from 1944 to 2015, the area of commercial forests decreased by 441.0 thousand ha. The reduction of the commercial forest area of group II and the allowable cut limitations imposed by the Cut Regulations brought about low intensity of forest utilization in Belarus as compared to other countries. Wood harvest volumes per unit of total volume comprised

9.7 and 13.0 m^3 per 1000 m^3 of total volumes in 2013 and 2016 respectively that is 1.4 times as little as in Poland, twice as little as in Austria and 3.8 times as little as in Finland.

The above mentioned factors have increased the values of annual total stock dynamics: 1983 – 20.0 million m^3, 2017 – 37.6 million m^3. Considerable changes in forest fund area are not predicted in the long-term perspective. The age structure of forest will remain non-optimal. The decreasing share of medium-aged stands will lead to significant reduction of wood volumes. The increasing share of mature forests will make it necessary to increase the allowable cuts regardless of the limitations prescribed by the new Forest Code (2015).

Experts estimate that 57% of the available mature stands will be cut until 2050. 22% of the wood volume is exempt from final cuts for nature conservation purposes. Considerable wood volumes are hardly accessible. Mature stands in the zones of radioactive contamination with ^{137}Cs density over 15 $Kukm^2$ are regarded as wood harvest reserves and are subject to cut restrictions. Under these conditions total average stock dynamics will decrease to 15–17 million m^3 or 2.5 times as little as of 01.01.2017. Contrary to the estimated figures for the upcoming decades, for the past 65 years carbon sequestration by the forest fund of the Republic of Belarus has amounted to 2 111 million t C and 7 740 million t CO_2 has been removed from the atmosphere. Annual carbon dioxide absorption has increased 2.53 times and amounted to 46 986 thousand t in 2017, i.e., 42% of industrial greenhouse gases emissions was compensated. This dynamics will cause the reduction of carbon dioxide absorption by forest fund so that specific compensatory measures will be required to maintain the values achieved in 2017.

10. Over the period from 1956 to 2017 the forests of Belarus have captured about 2 111 million t of atmospheric carbon with subsequent sequestration in phytomass and soils of the forest fund. This amount can be compared to the "stock" (absorption) of nearly 7 740 million t CO_2. Over the same period the increment of CO_2 ("emission") in the earth atmosphere amounted to approximately 420 billion t, so the sustainability of carbon sequestration capacity of Belarusian forests deserves high appreciation. Carbon balance of the forest fund is not time-stable due to the dynamics of wood stock and the level of forest utilization. Carbon budget can be altered by the following factors:

reduced areas of forested lands, changing age structure of forests due to increasing areas of mature and ripening stands, increased wood harvest by final fellings, regeneration cuts, conversion and other cuts. These factors are also able to redirect the net flow of carbon into the atmosphere. Carbon flow monitoring and mechanism of their calculation are important tasks of the forest sector. Predominating "emission" in the carbon balance of the Belarusian forest ecosystem can adversely affect the national forest sector under the conditions of globally rising pressure in the field of carbon dioxide emission into the atmosphere. Sustainable and dynamic development of forestry in the Republic of Belarus creates good conditions for maintaining the same dynamics of forest fund both in the short-term (until 2030) and long-term (until 2050) prospects. Whereas the total area of the forest fund will remain unchanged (9 565.8 thousand ha), the forested lands are predicted to increase until 2030 (+80.6 thousand ha) with the total wood increment of 47.4 million m^3. Steady wood harvest volumes can ensure stabilized carbon budget in the forests of Belarus.

Wood harvest is estimated to increase by average 1694 thousand m^3 until 2030 as compared to 2017. Consequently the level of annual carbon dioxide absorption is expected to decrease by average 1708 thousand t annually. Estimated carbon removal from the forest fund of the Republic of Belarus due to wood harvest will amount to 6523 thousand tC for 2018-2030 that is equal to carbon dioxide "emission" of 23912 thousand t CO_2 due to wood harvest, including 7874 thousand t CO_2 for 2018–2025 and 16038 thousand t CO_2 for 2026–2030. The declining tendency of carbon stock contradicts the national policy in the field of climate change mitigation. The forest sector must compensate the CO_2 emissions from wood harvest by means of measures to increase the carbon sequestration capacity of forests. In this way, the present level of the carbon dioxide absorption will be maintained. Responsible forest management and efficient actions that can affect carbon flows can increase the level of carbon dioxide absorption by the forest fund of Belarus.

11. National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030 has been drafted. The National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030 is an implementation mechanism of the United Nations Strategic Plan for

Forests for 2017–2030 (UNSPF) with regard to the global forest goal 1.2 “The world’s forest carbon stocks are maintained or enhanced” and a contribution of the forest sector of the Republic of Belarus to Sustainable Development Goals (SDG) as a member country of Sustainable Forest Management (SFM). This National Plan is a contribution of the forest sector into the implementation of Presidential Decree of the Republic of Belarus No.345 dated 20.09.2016 by which Belarus committed to the Paris Agreement with pledge to reduce greenhouse gases emissions.

The National Plan specifies forestry actions within the State Program of Measures on Climate Change Mitigation for 2013–2020 approved by the Resolution of the Council of Ministers of the Republic of Belarus No.510 dated 21.06.2013. The National Action Plan covers the review and intended actions and measures to be taken by the forest sector. The Action Plan contains the following chapters: general provisions; forests of Belarus as a source of carbon dioxide absorption; estimation of the level of the carbon dioxide absorption by Belarusian forests until 2030; strategy for increasing the level of the carbon dioxide absorption by Belarusian forests; measures of the National Action Plan on increasing the carbon dioxide absorption. Mandatory provisions of the National Action Plans include institutional environment; scope of work to increase the level of the carbon dioxide absorption; expected outcomes on increasing the annual carbon dioxide absorption resulting from implementation of the National Action Plan developed within this task

12. Strategic goals of the forest sector aimed at enhancing its role in the climate change management in the XXI century by means of carbon dioxide absorption by the forest fund should include the following actions and measures.

Measures to improve the institutional framework of forest sector actions on increasing the carbon dioxide absorption include: development of the sectoral program for increasing of average density of forests; entry of the following data into the Forest Cadastre: total carbon amount of the forest fund, phytomass carbon of the forest fund, total dynamics of carbon sequestration by the forest fund; entry of the following provision into the “Regulations of determination and approval of allowable final cuts in the forests of the Republic of Belarus”: carbon weight sequestered by wood of the established allowable cut volume shall not exceed annual carbon absorption achieved by the planned targeted actions on increasing the carbon sequestration capacity of forests and non-forested lands of the forest fund; Supplementing forest management plans with the section “Measures on increasing the level of carbon dioxide absorption by forest fund”; Development of TCCP “Rules of calculation of greenhouse gases absorption and emission by forest fund components”; Development of databank “Swampy forests of transition and raised types that are exploitable, unsuitable for logging, used for carbon sequestration”; Entry of the following provision into the Fellings Regulation of the Republic of Belarus: final cuts are not allowed in swampy forests of transition and raised types used for carbon sequestration and biodiversity conservation.

Forest sector measures to increase carbon dioxide absorption include: change of forest management regime in swampy forests of transition and raised types into nature protection regime – 10%; creation of forest plantation by ball-rooted nursery stock – 2,8%; partial final cuts – 3,2 %; restoration of low-graded forest stands – 2,5%; energy uses of wood harvested from debris-strewn forest – 20%; energy uses of logging residues from final and other felling sites – 23%; support for natural regeneration in ripening and mature forests – 2,5%; iIncrease of average density of stands as compared to 2017 +0,016 (2025) and +0.044 (2030) – 30%; long-term withdrawal of certain forest areas from forest management – 9,2%.

13. Estimated level of carbon dioxide absorption by the forest fund of the Republic of Belarus amount to 47012.9 thousand t CO_2/year for 2025 and 47249.0 thousand t CO_2/year for 2030. These figures exceed the corresponding level of 2017 by 0.06% and 0.56% respectively. The achievement of these estimated figures is a relevant goal of the forest sector of the Republic of Belarus. This will lead to the achievement of the goal of the National Action Plan, i.e., maintenance of the achieved level of annual carbon dioxide absorption by the forest fund under the conditions of increased (41.4%) annual wood harvest by final felling, regeneration cuttings, conversion and other fellings until 2030.

14. The draft National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030 has been submitted for approval to the concerned public administration bodies,

representatives of logging and woodworking sectors, scientific community, nature protection and non-governmental organizations that were recommended by the Ministry of Forestry of the Republic of Belarus.

On February 08, 2018, Belarusian State Technological University held a presentation of "Strategy and Action Plans for the Adaptation of the Belarusian Forestry Sector to Climate Change and to Implement the Principles of "Green Economy"" and roundtable discussions under the Republic of Belarus Forestry Development Project. One of the roundtable discussions was devoted to the National Action Plan on Increasing the Carbon Dioxide Absorption by the Forest Fund of Belarus. The report on the subject matter was made by L.N. Rozhkov, professor, D.Sc. (Agriculture), manager of Task 2 "National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030" under Contract No. BFDP/GEF/CQS/16/25-26/17 dated October 23, 2017.

The plenary session of the event included a report by I.V. Voitau, BSTU rector, consultant under Activity 3.1.4 "Consultancy Services to Develop Strategies and Actions Plans for the Adaptation of the Belarusian Forestry Sector to Climate Change and to Implement the Principles of "Green Economy"". The report was discussed by numerous event participants such as A.A. Kulik, First Deputy Minister of Forestry of the Republic of Belarus; Alexander Kremer, World Bank Country Manager for Belarus, L.I. Maksyutenko, Advisor of Scientific and Innovation Activities Department of the Ministry of Education of the Republic of Belarus; M.I. Khalimov, Deputy of Security Cooperation and New Challenges Counteraction Department of Commonwealth of Independent States Executive Committee; L.G. Makurov, Head of ROSSOTRUDNICHESTVO Office in Belarus, First Secretary of Russian Embassy in Belarus, Yu. V. Solovyev, National Coordinator of Small Grants Programme of Global Ecological Facility in Belarus.

The report by L.N. Rozhkov was held within the roundtable discussion with active participation of representatives of the following departmetns and organizations: Forestry Department of the Ministry of Forestry of the Republic of Belarus; Main Department of Sustainable Developemnt of the Ministry of Economy of the Republic of Belarus; Department of Air and Climate Change Impact Control and Expertise of the Ministry of Natural Resources and Environmental Protection of the Republic of Belarus; Institute of Experimental Botany under the National Academy of Sciences of Belarus; Republican unitary enterprise “Bellesexport”; Republican forest selection and seed centre; Republican unitary enterprise “Belgosles”; Republican Professional Development Centre for Managers and Professionals of the Forest Sector; Negoreloe Forestry Experimental Station; “Ekomir” Fund; Scientific and Practical Centre for Bioresources under the National Academy of Sciences of Belarus; Belarusian Forest Newspaper; journalists of Radio Channel 1 and “Stolichnoye Televideniye” TV Channel; “Bagna” NGO; “Rodnaya Pryroda” journal; researchers, teachers and students of Belarusian State Technological University. The total number of participants was 62. Questions were asked by 12 attendees, 3 participants contributed to roundtable discussion.

The roundtable discussion participants expressed their support to the National Action Plan on Increasing the Absorption of Greenhouse Gases by Sinks (Forests, Swamps) until 2030. It was recommended to submit the amended National Action Plan to the Mnistry of Forestry, other public administration bodies of forest management and concerned Ministries and departments for further approval and practical implementation in the forest sector. The task manager has revised and amended the National Action Plan in accordance with the comments made by the roundtable discussion participants.

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