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Consideration of Ecosystem Functions in Assessing the Condition of Natural Capital in the Northern Region

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Abstract. The concept of natural capital goes beyond nature as a source of raw materials for production and includes consideration of the environment and ecosystems condition in maintaining human well-being. For sustainable resource use, it is first necessary to determine the stability of ecosystems to a variety of anthropogenic and technogenic loads. The natural capital of forests includes not only forest (primarily wood) resources, but also the full range of ecosystem services, associated with a healthy habitat. The aim of the study is to assess the condition of ecosystems in the active forestry zone of the Komi Republic due to the long-term use. The novelty of the study lies in identifying the degree of ecosystem stability in this area of the region. We use general scientific methods of analysis, synthesis, comparison, generalization, computer-cartographic form tools, based on the use of ArcView program. Assessment of natural capital components made it possible to differentiate forestry according to the positions "biodiversity conservation", "water regulation", "water protection", "carbon sequestration"; to identify the nature of restrictions and recommend the operation mode, taking into account the necessary environmental protection measures and reduction of anthropogenic load. The relative stability of the ecosystem over the period 2000–2020 was revealed. Threats are expressed in a slight reduction of biodiversity, weakening of groundwater flow accumulation and surface runoff accumulation functions due to intensive logging of low-age forest species. The predominant part is classified as an area of favorable ecological condition, where different operation modes are proposed. However, in a number of forestries there is a situation, when the ecosystem is under strong pressure, which caused a decrease in the stability of the three positions of ecosystem services and

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characterizes an unfavorable condition of the ecosystem. In this case, a particularly strict operation mode of forest ecosystems with maximum reduction of logging is recommended. Prospective studies are related to the cost estimation of ecosystem services to analyze the possibility of compensating funds for nature restoration in relation to large loggers in the region.

Key words: ecosystem services, biodiversity conservation, assessment of water protection and water regulating functions, carbon sequestration capacity, ecosystem accounting, forest management, Komi Republic.

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Introduction

The interest in assessing elements of natural capital, where ecosystem services are one of the important links, began to emerge more than 30 years ago with the understanding of the need to fulfill the principles of sustainable development. Awareness of the ecosystem functions' value, their impact on people's standard of living and the state of ecosystems often associated with their depletion determined the beginning of painstaking activities of various assessment (ecological, economic, social) and its embedding in ecosystem accounting for making management decisions (Ruqian Zhang et al., 2023).

Approaches to measuring ecosystem services can be expressed in monetary units, units of time and labor or relative indicators. These include, for example, the number of people using these services, their preferences, the cost of obtaining or maintaining access to the service, and the availability and cost of substitutes[1].

Ecosystem accounting accumulates a complex of information on the state of ecosystems: measurements (in units); changes (in dynamics) and assessments of the impact of human economic activity. In modern conditions, it has become widespread both at the spatial level of territorial objects (forestries, municipal districts, specially protected natural areas) and at the level of enterprises and corporations, etc.[2]

Scientific and scientific-practical interest in approaches to studying and ecosystem functions assessment has been observed in the last decade under the auspices of a number of projects and cycles of publications by Russian and foreign authors (Kripa et al., 2023; Lilford, 2023). The emergence of several volumes of the "Prototype of the National Report" on state specifics, ecosystem function assessment and use practices confirms the relevance of this issue in Russia (Ecosystem Services ..., 2016, Ecosystem Services ..., 2020, Ecosystem Services ..., 2021). Based on the rich international experience, the introduction of adaptive forms of environmental management tools, the practical use of accounting for ecosystem functions is beginning

[1] System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA). Available at: https://seea.un.org/ecosystem-accounting

[2] System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA). Available at: https://seea.un.org/ecosystem-accounting; Developing Corporate Natural Capital Accounts. Guidelines for the Natural Capital Committee. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/516971/ncc-research-cnca-guidelines.pdf; Natural Capital Account 2019–2020. Forestry England. Available at: https://www.forestryengland.uk/sites/default/files/documents/Natural%20Capital%20Account%202019-2020_0.pdf; UK natural capital accounts: 2022. Estimates of the financial and societal value of natural resources to people in the UK. Available at: https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/uknaturalcapitalaccounts/2022

to form in Russia (Accounting and Assessment..., 2014; Burkhard, Müller, 2013; Syrbe et al., 2013). Categories such as potential volume of services, potential volume of use and real demand in physical and value units are subject to accounting in international practice[3] (Zegeye et al., 2023). Mapping and scenario development methods for ecosystem exploitation are used for this purpose (Syrbe et al., 2013; Accounting and Assessment ..., 2014). Conflict resolution, impact assessment in the design and construction of facilities that negatively affect the state of the natural environment in the long term, is demonstrated by analyzing the state of ecosystem functions[4] (Tishkov, 2010).

Over the last decade, the global practice of natural capital accounting at the object level for large corporations has become increasingly common. This has led to the emergence of the Natural Capital Assessment Protocols[5], the ISO Environmental Finance Assessment Standards – ISO 14008 and ISO 14007 and the ISO 14044 Life Cycle Assessment Standards and the Ecosystem Accounting System[6].

The UK has been a leader in the practice of assessing and accounting for natural capital assets. For example, starting with the development of a methodology for corporate assessment of natural capital (2015), BS 8632 natural capital accounting for organizations was adopted in 2021 and in 2022 guidance on the assessment of natural capital ecosystem services for UK forestry was adopted. Production services (wood resources, wood fuel), but also a wide range of regulating services (carbon sequestration, pollutants, water regulation, cooling effect of parklands) and cultural services (tourism, health effects of being outdoors) will be subject to cost accounting[7].

Natural capital valuation documents are necessary for companies to understand and ultimately manage their risks and opportunities. The results of such assessments are intended for internal decision making, not for disclosure. Companies can appropriately inform their stakeholders about capital management and integrate it into their development strategies. This also allows a company to integrate information in the same way and show how different capitals are important for its long-term viability (Dmitrieva, 2022).

The Russian example of implementation of the state of eco-services analysis (environmental protection, water regulation, etc.) in physical and cost units is demonstrated in the entities' Forest Plans and includes information at the time of their compilation and for the future.

There are examples of individual ecoservice assessments in the region, which only confirms the long-standing interest in them (Likhanova, 2012; Tikhonova, 2017; Ptichnikov et al., 2019). However, the assessment of their state in the complex of several ecosystem functions and in the dynamics over a long period of impact on the natural environment has not been considered.

The Komi Republic is one of the significant regions for logging. It has a vast area (36.3 million hectares, or 87% of the territory) and almost a century of exploitation history. At present there are

[3] Technical Recommendations in support of the System of Environmental-Economic Accounting 2012 – Experimental Ecosystem Accounting (2019). Available at: https://seea.un.or/content/technical-recommendations-support-seea-eea

[4] Methodology for determining the valuation of ecosystem services and the value of biological diversity. Technical Code of Established Practice (2010). Bel NITS "Ekologiya". Minsk.

[5] Natural Capitals Coalition. Natural Capital for Biodiversity Policies: What, why and how. Available at: https://capitalscoalition.org/wp-content/uploads/2021/04/Natural-capital-for-biodiversity-policy-%E2%80%94-FINAL-1.pdf;

Natural Capital Coalition. Natural Capital Protocol. Available at: www.naturalcapitalcoalition.org/protocol;

Natural Capital Coalition. Natural Capital Protocol: Forest Products Sector Guide (2018). Available at: https://naturalcapitalcoalition.org/wp-content/uploads/2018/07/NCC_ForestProductsSectorGuide_Web.pdf

[6] System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA). Available at: https://seea.un.org/ecosystem-accounting

[7] Office for National Statistics, ONS website, methodology, Woodland natural capital accounts methodology guide. Available at: https://www.ons.gov.uk/economy/environmentalaccounts/methodologies/woodlandnaturalcapitalaccountsmethodologyguideuk2022

32 forestries, 24 of which belong to the zone of the most active use of forest resources8. The main areas and volumes of harvesting are concentrated here (more than 60% of the timber stock and more than 90% of the volume of harvested timber).

The current management conditions are characterized by the use of modern harvesting equipment, and forest management system based on the principles of sustainable resource use (Forestry ..., 2000). Therefore, the estimated period of the study (2000–2020) was chosen.

The aim of the study is to assess the ecosystems' state due to long-term exploitation of the territory of the active forestry use zone of the Komi Republic. Analysis of calculations of changes in ecosystem service flows and the influence of various influencing factors will make it possible to differentiate forests according to the degree of ecosystem suitability and sustainability of ecosystem service provision. On the basis of such differentiation, it will be possible to substantiate recommendations on the nature of permissible exploitation modes for the resources of the study area, which are the main objectives of the study. The novelty lies in the identification of the ecosystem sustainability degree in the territory of the most active logging activity of the Komi Republic. The territorial units of the study are municipal districts and forestries.

Research methods

The study was based on the methods of theoretical (generalization, comparison, systematization) and empirical analysis (statistical observation, graphic interpretation). Based on the ranking of ecosystem functions, the most important ecoservices for forest systems such as, biodiversity conservation, water regulation, water conservation and carbon sequestration were selected. The work of T.V. Tikhonova (Tikhonova, 2022) was devoted to the analysis of the choice of indicators for assessing these services. Time slices of the basic period of the study (2000–2020) are adjusted by the dates of availability of necessary information.

Biodiversity is assessed by the number of taxons that are identified on the territory of forestries (mainly on the protected areas). Information is contained in the editions of the Red Book of the Komi Republic (1998 and 2019). The analysis of species diversity conservation considered changes in the number of rare species, the distribution area by forestries and rarity status.

The study emphasizes the consideration of anthropogenic and forestry factors. In addition, the reliability of the information and the study of the territory are assessed. The main indicators characterizing anthropogenic pressure are population density, transportation network density and logging intensity (ratio of average annual volume over a twenty-year period to the forest area covered). The territorial unit of the study of impact factors is municipal districts. The information base was statistical collections on the Komi Republic for the period under study.

The water regulating function of the forest is calculated from the accumulation of runoff in the underground horizons. The product of the groundwater flow increase and the area of forest plantations on the territory of forestries determines the volume of water accumulation in underground horizons. The area of forest plantations is taken according to the data of forested areas of the forest fund of forestries.

The value of average annual groundwater flow increase ΔS (mm) is calculated by the formula:

$$\Delta S = X \times \alpha \times K_1 \times \mu \times [C_1 \times K_2 \times K_3 \times K_4 - C_2]. \quad (1)$$

The value of average annual precipitation X and the share of summer precipitation μ is taken from the Climate Handbook and "Building Climatology" Building code. The correction factors used to calculate the average annual increase in groundwater flow are based on the studies of Yu.V. Lebedev and

[8] On the state of the environment of the Komi Republic in 2021 (2022): State report. Syktyvkar: Ministry of Natural Resources of the Komi Republic.

I.A. Neklyudov (Lebedev, Neklyudov, 2012). The value of the flow coefficient (α) is determined depending on the natural vegetation zone of the area and the terrain. The value of coefficient C_1 depends on forest cover, type of plantations and mechanical composition of soils (Lebedev, Neklyudov, 2012). The value of the coefficient C_2 for the non-forested area is taken at the level of 0.2. Correction coefficients K1-K4 are established depending on the wetland area, age, bonitet and completeness of forest plantations. The calculation is carried out by age groups of coniferous and deciduous plantations. Forest characteristics for calculations include bonitet, age and completeness of forest plantations according to the data of the State Forest Register and departmental reporting forms of the Ministry of Natural Resources of the Komi Republic for 2008 and 2020.

The water protection role of a forest ecosystem is assessed by the magnitude of change in surface runoff due to an increase or decrease in forest cover (Economy of Conservation ..., 2002). The dependence of these values is determined by the equation:

$$M = -1.02 + 0.068 \times F, \quad (2)$$

where M – module of runoff from 1 km^2 of the drainage basin (thousand cubic meters/ha), F – forest cover of the territory (%).

The area of forest plantations is taken according to the data of forested areas of the forest fund of forestries, respectively, the forest cover of the territory of forestries is calculated as a share of forest plantations from the total area of the forest fund of forestries. The runoff volume is determined by the multiplication of the area of the forested area of the forestries and the runoff module. The information base includes forms of the State Forest Register and departmental reporting of the Ministry of Natural Resources of the Komi Republic for 2000 and 2020.

Analysis of the length of water protection zones, which fulfill the role of watercourse protection, is also assessed as an addition to the calculations. The source of information was reports of the Ministry of Natural Resources of the Komi Republic for 2007 and 2021.

For the forest ecosystems of the region on forestries, it is acceptable to calculate *carbon sequestration* using specific indicators of absorptive capacity of boreal forests (Dolman et al., 2012). The forested areas of the forest fund of forestries are taken from the forest management data for the basic years of the study (2000 and 2020).

Values of ecosystem service indicators are expertly categorized into groups of decreasing ecosystem function and different growth intensities. A complex nature of the analysis is made up by a matrix that accumulates these groups by forestries.

Results of the assessment

Biodiversity. The selection of species for biodiversity state assessment is based on uniqueness, indicativeness and logging activities as a threat to existence. According to these criteria, the following groups of organisms were considered for 145 taxons from the two Red Books data of the region: lichens (46 taxons), vascular plants (47 taxons), fungi (23 taxons), mosses (12 taxons), insects (10 taxons), reptiles (3 taxons) and birds (4 taxons), whose status is varied (from "1" to "4"). Conservation of biodiversity was considered through changes in the number and status of rare species, and their distribution areas by forestries.

The analysis of the situation showed that the exploitation of forest areas had an insignificant impact on the number of species populations and was reflected only in the disappearance of rare lichen species on the territory of a number of forestries with high intensity of logging activities. Thus, forest management in the territory of the Priluzskoe, Kazhimskoe, Letskoe, Koigorodskoe, Syktyvkarskoe and Pechora-Ilychskoe forestries has resulted in the disappearance of rare lichen species, which is an unfavorable situation for ecosystem conservation.

Changes in natural and climatic conditions and conditions for comfortable existence of rare species of birds and insects contributed in most cases to the transfer to a milder category, which indicates the prevalence of species.

Despite the fact that fish are not among the species threatened by logging, this activity still negatively affects the volume of river runoff, especially in small watercourses, through siltation processes, creating uncomfortable conditions for existence. Therefore, it should be noted that rare fish habitats with changes in population numbers are observed in water bodies of a number of forestries in the middle reaches of the Mezen River, the main channel of the Vychegda River and the lower reaches of its tributaries (Vym, Sysola, Vishera and Lokchim). And on this territory the situation is favorable, but with the initial level of reduction of sustainability. On the territory of other forestries there is a favorable situation for the conservation of ecosystems and biodiversity.

The main factors determining biodiversity conservation, taking into account intensive logging exploitation of the area, are:

– natural (climate, natural disasters, diseases);

– anthropogenic (production, population, transport infrastructure);

– forestry (implementation of forest certification; conservation of intact forest areas);

– informational (monitoring of ecosystems state, data reliability).

The present study emphasizes on the consideration of anthropogenic factor.

Anthropogenic factors. The intensity of logging activities is different across the districts and varies with a 25-fold difference from 0.06 cubic meters/ha to 1.5 cubic meters/ha.

The analysis of statistical data by districts in 2000 and 2020 showed a decrease in the anthropogenic load of population density for the entire area. It should be noted that a decrease in population density does not always proportionately reflect the level of resource withdrawal and other negative effects on forested areas. Ecological literacy and people's desire to preserve nature are very important here. The expert assessment fixes the increased load of fish and hunting resources withdrawal regardless of the population decrease and its density on the territory of Ust-Vymsky, Troitsko-Pechorsky and Udorsky districts.

Human economic activities and transport routes contribute to the spread of negative effects such as the introduction of invasive species. At present, 170 such plants have been recorded in the forest zone of the republic, including the following plants: Amaranthus retroflexus, Echium vulgare, Lepidium latifolium and others. Of particular concern is the emergence of dangerous quarantine weeds – Ambrosia artemisiifolia, Lactuca tatarica, Rhaponticum repens. At the same time, Typha, Melilótus, came from cultivated plantings of Lupinus and Heracléum sosnówskyi, are assimilated by the natural flora.

Logging roads in the Komi Republic are represented by sand and gravel roads and concrete tracked roads, and also by plank roads of year-round operation, snow and ice roads used in winter and narrow-gauge railroads. The main transport routes used for transportation of harvested timber in forestries are public roads and specialized roads built by loggers.

Year-round roads are an important factor in negative impacts on biodiversity due to the period of use and soil disturbance during construction. The maximum growth of transportation network density is observed in the territory of Koygorodsky (4.9-fold), Troitsko-Pechorsky (1.7-fold), Ust-Kulomsky (1.6-fold) and Priluzsky (1.4-fold) districts.

A summary of the aggregated anthropogenic load by logging intensity activity, population density and transportation network for the entire study period is shown in *Table 1.*

Orange color marking indicates increased load; yellow color shows average load and green color –

Table 1. Characteristics of anthropogenic load of the intensive forest exploitation area for the period 2000–2020

Municipal district	Average annual logging intensity for the period, m³/ha	Population density, people/thousand ha		Road density, km/thousand ha	
		2000	2020	2000	2020
Sysolsky	1.50	30.47	20.10	0.84	0.97
Priluzsky	1.27	21.11	12.45	0.37	0.53
Syktyvdinsky	1.00	37.01	32.85	0.63	0.61
Koygorodsky	0.70	9.60	6.91	0.15	0.71
Ust-Kulomsky	0.65	13.88	8.80	0.36	0.59
Kortkerossky	0.51	13.17	9.01	0.29	0.36
Ust-Vymsky	0.33	80.21	51.31	1.30	0.86
Udorsky	0.23	8.35	4.63	0.34	0.32
Troitsko-Pechorsky	0.09	4.85	2.54	0.09	0.15
Knyazhpogostsky	0.06	12.80	7.52	0.29	0.24

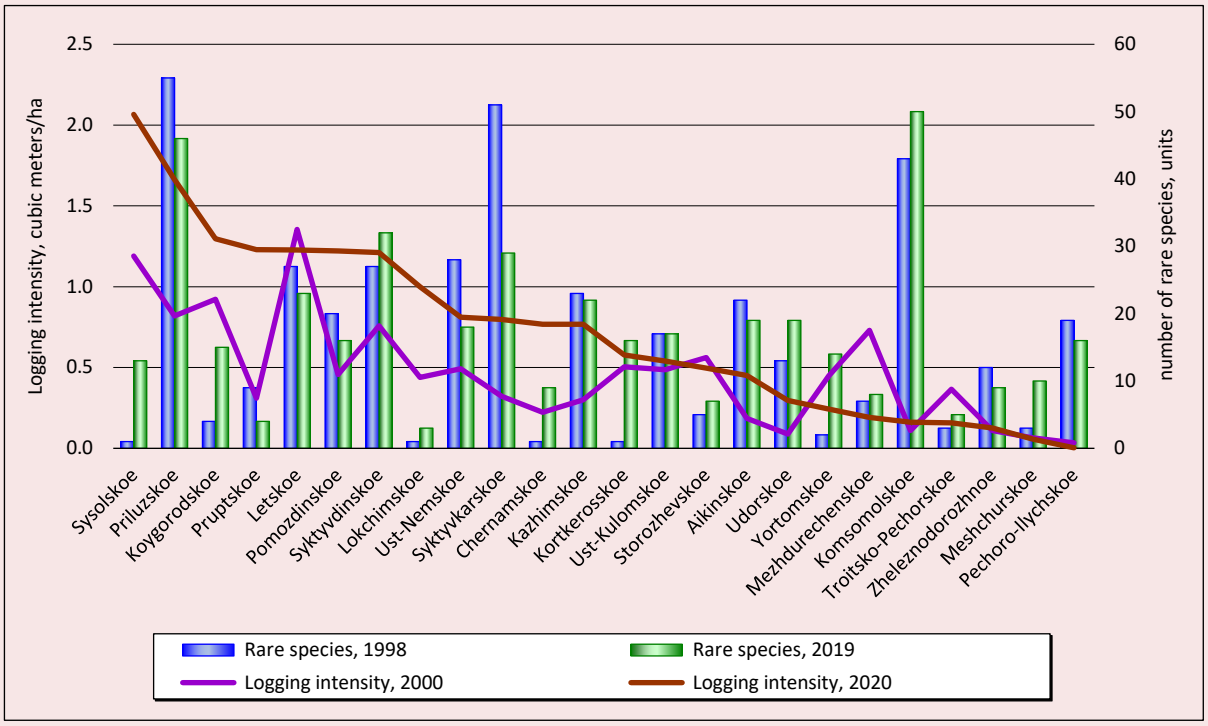
Own calculations based on the forest management data. Committee of forests of the Komi Republic; Socio-economic situation of cities and districts of the Komi Republic: Statistical collection. Komistat. Syktyvkar, 2021; Urban okrugs and municipal districts of the Komi Republic. Socio-economic indicators: Statistical collection. Komistat. Syktyvkar, 2021.

minimum load. According to the combination of three factors, we can note that the maximum anthropogenic pressure is observed on the territory of Sysolsky and Syktyvdinsky districts.

Changes in the number of rare species were recorded in most of the territory (*Fig. 1*).

A decrease in the number of rare species is observed on the territory of those forestries that

Figure 1. Impact of logging activities intensity on biodiversity conservation



Source: own analysis.

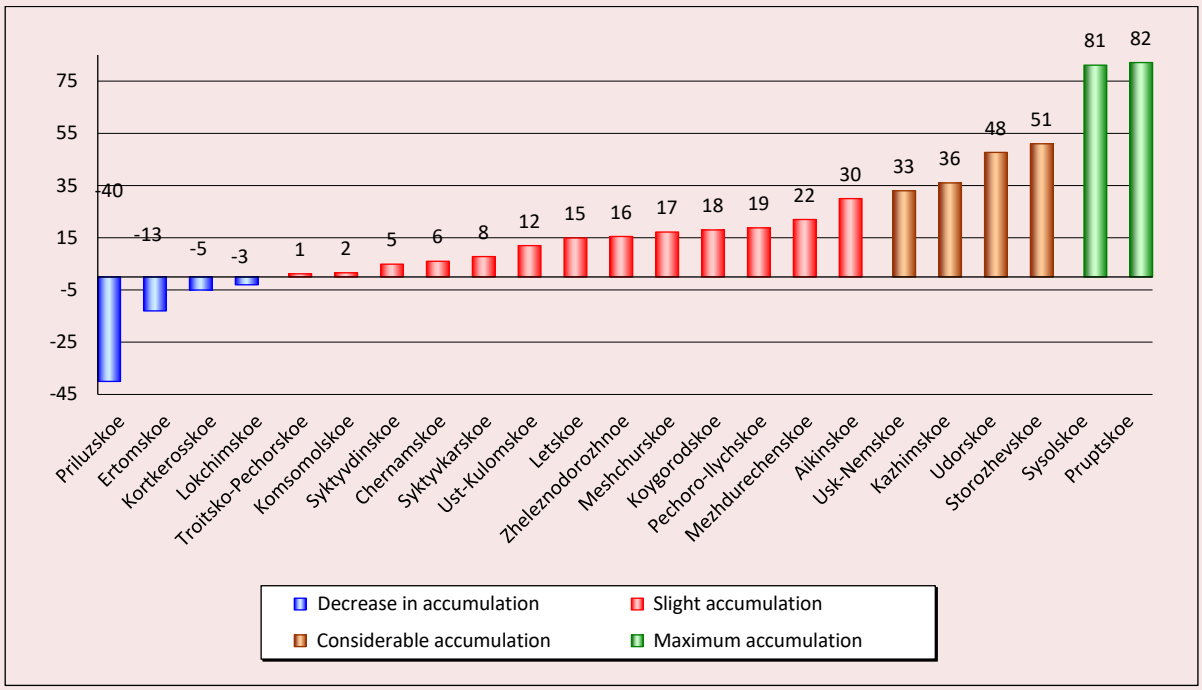
are as close as possible to the main center of raw material processing – Syktyvkar – and are more thoroughly studied – Priluzskoe, Letskoe, Kazhimskoe, Aikinskoe, Ust-Nemskoe, Pomozdinskoe, Zheleznodorozhnoe and Pechora-Ilychskoe. The influence of logging intensity on the decrease in the number of rare species is observed in isolated cases of long-term logging (in Koigorodskoe, Priluzskoe, Syktyvkarskoe forestries).

Another category of change is the increase in the number of rare species, that is, their distribution. The main reasons for this situation in Sysolskoe, Koigorodskoe, Chernamskoye, Ertomskoe and Komsomolskoe forestries are in the knowledge and monitoring of the territory and relatively low anthropogenic load.

The results of assessment of water regulating function in the districts of the active forest management area of the region showed, that the main factors of growth were increase of average annual total precipitation, change of bonitet and areas occupied by young and middle-aged coniferous species. Differentiation of groundwater flow growth by forestries due to changes in forest characteristics is presented in *Figure 2*.

As we can see in Figure 2, a decrease in runoff accumulation in underground horizons is observed in four forestries. At the same time, the increase in the total area of forest plantations does not affect the runoff volumes. The main reason for such changes is the reduction of bonitet in the age structure of species, both coniferous and deciduous plantations. For example, on the territory of Priluzskoe forestry the bonitets of young and middle-aged species changed from category II in 2008 to category III–V in 2020, which made adjustments in the reduction of groundwater runoff accumulation (-40.0 million cubic meters). The reduction of middle-aged species areas during this period also affected the value of groundwater flow volume.

Figure 2. Increase in groundwater runoff of forestries for 2008–2020, million m3



Source: own analysis.

Water regulating function. The increase of runoff in rivers is due to increase of forest area and forest cover in general in forestries. Accordingly, the decrease in runoff volume is due to the reduction of forest areas. During the study period, water bodies of most forestries did not reveal significant runoff losses. However, due to the reduction of forest areas and forest cover on the territory of a number of forestries there was a decrease in runoff accumulation in water bodies.

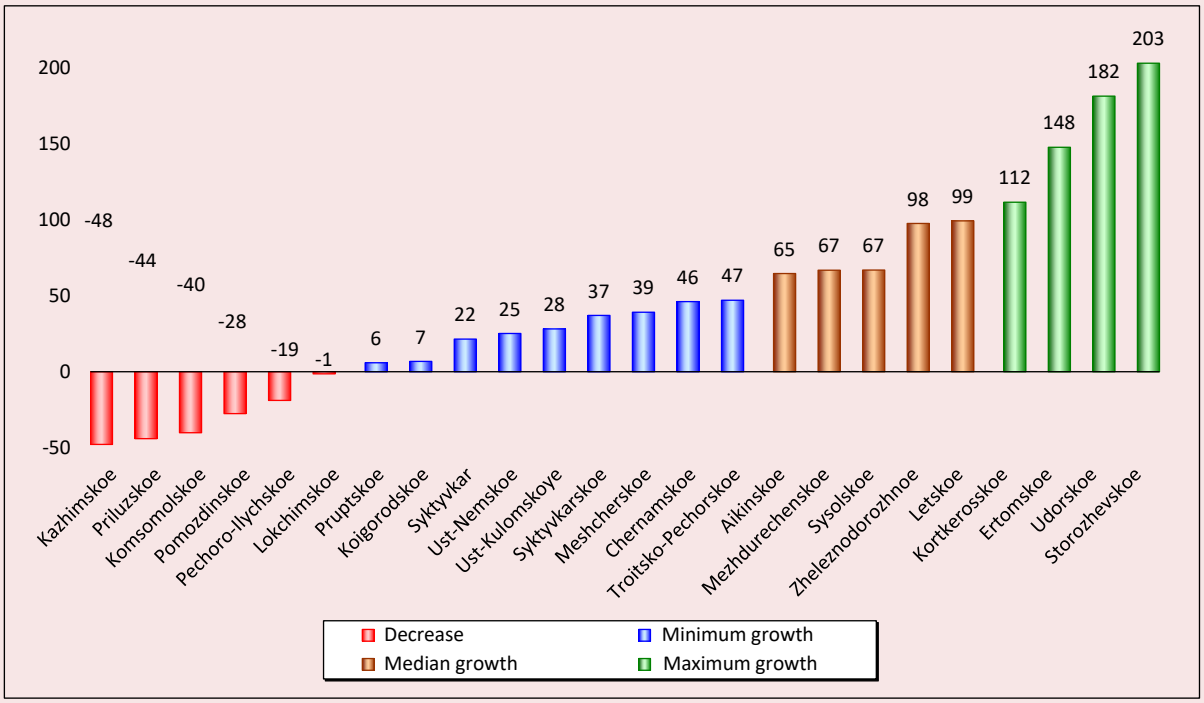
Differentiation of surface runoff growth by forestries due to changes in forest characteristics is presented in *Figure 3*. The maximum increase in surface runoff on the territory of four forestries is provided by increasing the area of forest plantations by 15–25 thousand hectares and forest cover by 1–1.5%.

Logging and forest area reduction affect water availability of small tributaries of the Pechora River on the territory of Komsomolskoe and Pechora-Ilychskoe forestries. There is no significant deterioration in surface runoff accumulation. Preservation of satisfactory condition of surface river runoff, its significant accumulation is observed on the territory of forestries of Udorsky and Kortkerossky districts due to significant areas of reserves (intact areas, including protected areas) and middle-aged coniferous forests.

Water protection strips along water bodies (rivers, streams and also lakes) belong to the area characteristics of water protection function. However, the information on these zones is determined by the length of their development.

Water protection zones along water bodies started to be improved in 2007 and covered only large rivers. Since 2013, annual statistics for large rivers and their tribu taries by municipal districts are given in the reports of the Ministry of Natural Resources and Environmental Protection of the Komi Republic.

Figure 3. Surface runoff increase in 2000–2020, million m^3



Source: own analysis.

Establishment of boundaries of water protection zones and protected shoreline belts on the ground in the priority order is carried out on water bodies, which are used for the purposes of drinking and household water supply in the areas located within the boundaries of settlements. The total length of the established water protection zones from 2007–2021 of the territory of intensive forest management is 2,448 km. The main purpose of their improvement is to ensure the safety of water supply to the population, so the share of organized water protection zones is extremely small in relation to the total length of the river network. According to the calculations, it does not exceed 1% of the river network length of each district, except for Ust-Kulomsky (3%) and Ust-Vymsky (5%). Thus, the most vulnerable are small watercourses, the organization and provision of protected belts of which lies entirely on the tenants of forest objects engaged in logging.

On the territory of most forestries there is an accumulation of groundwater runoff of large rivers: Vychegda, Vym, Pechora and their tributaries. Felling that led to changes in the bonitet and completeness of coniferous and deciduous plantations was especially evident in Priluzskoe, Ertomskoe, Kortkerosskoe and Lokchimskoe forestries. The intensity of groundwater flow accumulation was more influenced by precipitation than by felling, therefore, almost everywhere there was an increase in accumulation of water storage in underground horizons. The short range of available statistical data (2008–2020) on the state of forest characteristics (bonitet and completeness of coniferous and deciduous species) does not allow us to identify significant changes or significant susceptibility of the forest to anthropogenic changes.

The water protection function of forests, expressed in the increase of accumulation of rivers' surface runoff, has maintained and increased its initial state for the majority of forestries during the study period. Logging was reflected in the reduction of river runoff of the main tributaries of the Sysola and Pechora rivers in the territory of Kazhimskoe, Priluzskoe, Pomozdinskoe, Komsomolskoe and Pechora-Ilychskoe forestries. Water protection zones of small watercourses located far from large settlements are not equipped, which increases the possibility of siltation of water sources.

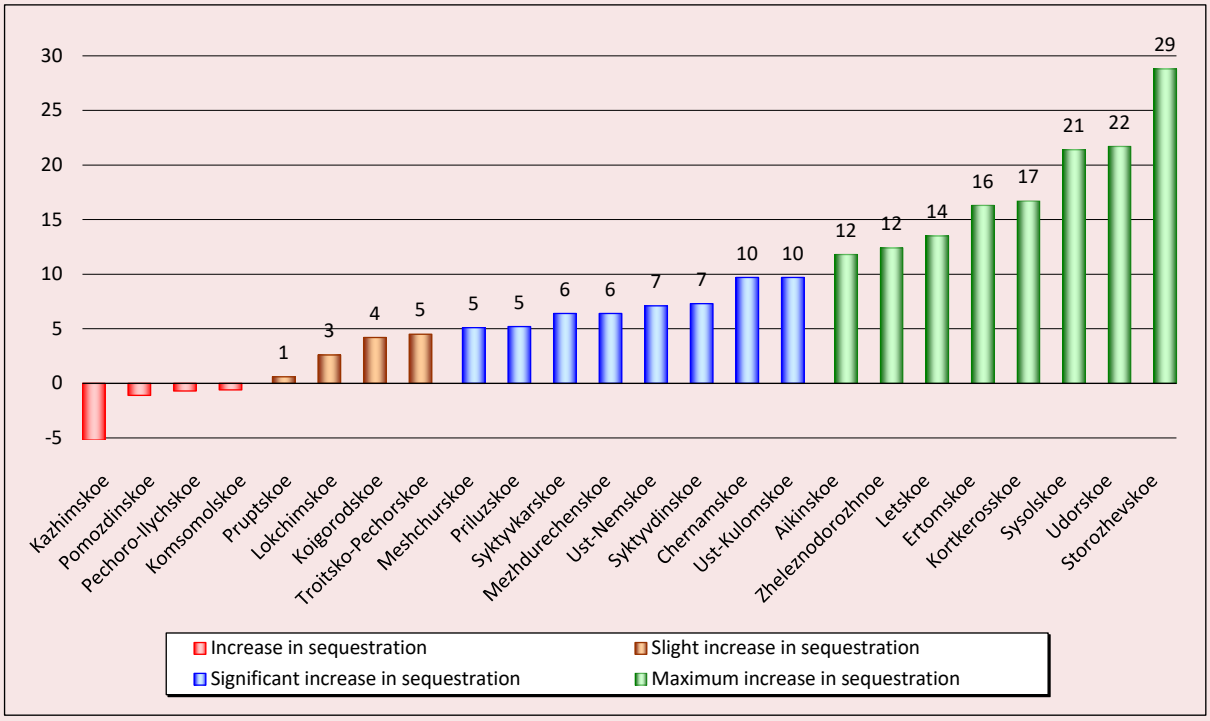
Most of the ecosystems of the forestries responded to logging in the same way by increasing the accumulation of groundwater and surface runoff. This situation is favorable and is typical for the following forestries: Letskoe, Koigorodskoe, Syktyvkarskoe, Syktyvdinskoe, Troitsko-Pechorskoe, Ust-Kulomskoe, Ust-Nemskoe, Chernamskoe, Sysolskoe, Aikinskoe, Udorskoe, Mezhdurechenskoe, Meshchurskoe and Zheleznodorozhnoe. In the rest of the area, there is either a reduction in runoff accumulation of both functions or one of the ecological services.

The change in the carbon sequestration capacity of forest ecosystems depends on the area of forests: the increment is due to the growth; the decrease is due to the reduction in the area of forest plantations. This approach to the assessment of carbon accumulation does not take into account the quality of forest plantations (age, completeness, bonitet), it partially reflects the real situation, allows us to identify the differentiation of the sequestration capacity of forests for twenty years of their exploitation (*Fig. 4*).

Carbon sequestration was calculated for forest ecosystems using specific absorptive capacity values of boreal forests at 1.15 tons CO2/ha (Dolman et al., 2012).

Calculations have shown that the carbon sequestration capacity of forests is increasing in most forestries. The forests of Letskoe, Sysolskoe, Kortkerosskoe, Storozhevskoe, Udorskoe, Ertomskoe, Zheleznodorozhnoe and Aikinskoe forestries have the maximum capacity, which is explained by a significant increase in the area of coniferous

Figure 4. Differentiation of carbon accumulation by forestries for 2000–2020, thousand tons



Source: own analysis.

Table 2. Reasons for maximum carbon sequestration during the study period

Forestries	Changes in forest characteristics
Letskoe	Increase in bonitet of young age structures of coniferous forest species; Increase in the areas of ripening age structures of coniferous and middle-aged deciduous species
Sysolskoe	Increase in bonitet of young and ripening age structures of coniferous species; Increase in areas of mature age structures of coniferous and deciduous species
Kortkerosskoe	Areas growth of young and middle-aged coniferous species
Storozhevskoe	Increase in bonitet of young age structures of coniferous forest species; Increase in areas of ripening and mature age structures of coniferous and middle-aged deciduous species
Udorskoe	Increase in bonitet of young age structures of coniferous forest species; Increase in areas of middle-aged coniferous species and mature age structures of deciduous species
Ertomskoe	Areas growth of middle-aged structures of coniferous and deciduous species
Zheleznodorozhnoe	Increase in bonitet of young age structures of coniferous species; Areas growth of mature coniferous species
Aikinskoe	Increase in bonitet of old-growth coniferous age structures; Increase in areas of middle-aged and old-growth coniferous and mature deciduous species
Source: own analysis.	

vegetation. In these territories, during the study period, there were positive changes in the bonitet of young and middle-aged coniferous and deciduous forest species, which have the maximum carbon sequestration capacity, and in the areas occupied by these species, which increased the intensity of carbon sequestration (*Tab. 2*).

In these areas during the study period there were positive changes in the bonitet of young and middle-aged coniferous and deciduous forest species, which have the maximum capacity for carbon sequestration, and in the areas occupied by these species, which increased the intensity of carbon sequestration.

Thus, almost the entire territory of the examined forestries has a high carbon sequestration capacity, and during the study period this capacity has not only been maintained, but also increased. The growth of carbon sequestration serves as an indicator of favorable condition of forest ecosystems.

Using the expert method, the entire zone of active forest management is divided into areas with decreasing favorability of ecosystems, and slight, moderate and significant growth of favorability according to the function of carbon dioxide absorption, water regulation of groundwater flow and water protection function, and the level of biodiversity conservation by forest ecosystems.

Discussion

The integrated assessment of accounting for the functions and benefits of nature allows us to summarize the results and present the overall level of sustainability by the degree of ecosystems' favorability to anthropogenic pressures over

Table 3. Types of ecosystem states of the territory of active forest exploitation and proposed operation modes

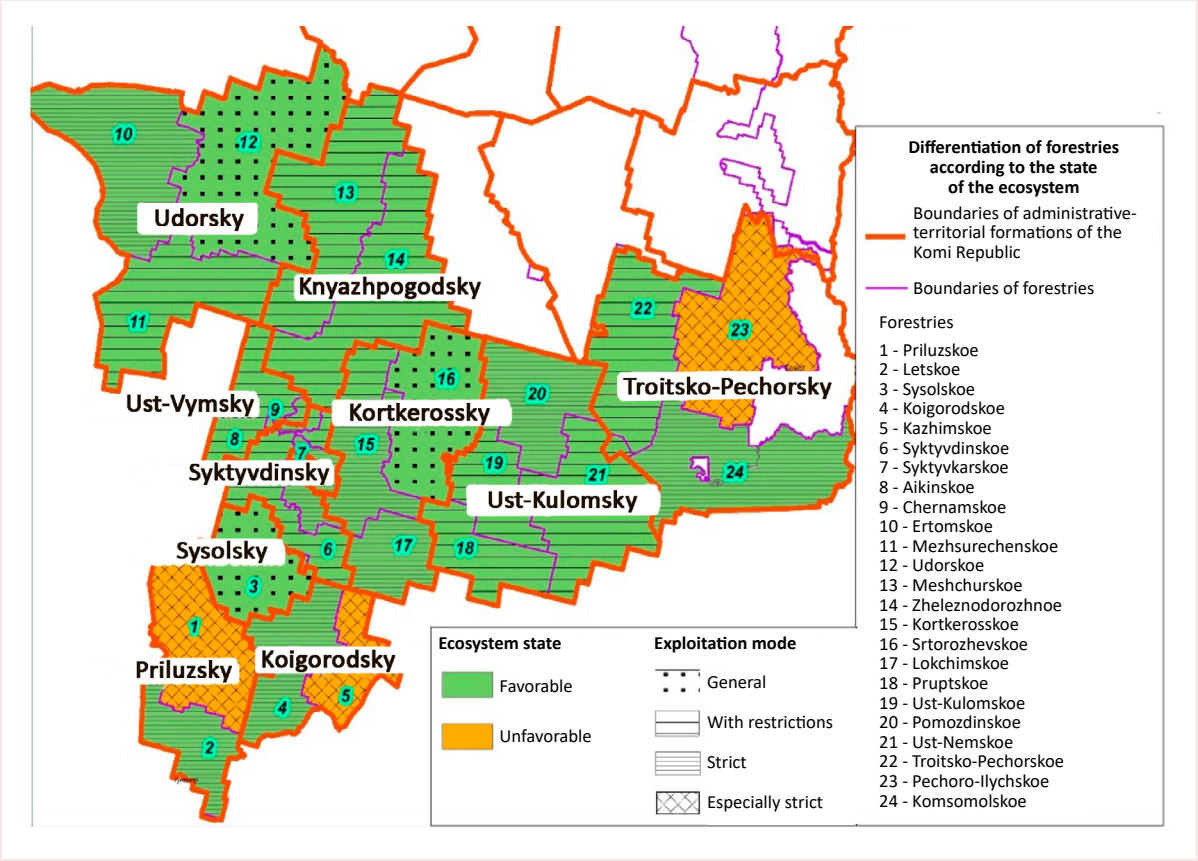
Forestries	Biodiversity conservation	Water regulation	Water protection	Carbon sequestration
Especially strict operation mode (unfavorable ecosystem state)				
Priluzskoe				
Kazhimskoe				
Pechora-Ilychskoe				
Strict operation mode (favorable ecosystem state)				
Pomozdinskoe				
Lokchimskoe				
Komsomolskoe				
Letskoe				
Koigorodskoe				
Syktyvkarskoe				
Ertomskoe				
Kortkerosskoe				
Operation mode with restrictions (favorable ecosystem state)				
Troitsko-Pechorskoe				
Ust-Kulomskoe				
Chernamskoe				
Ust-Nemskoe				
Meshchurskoe				
Syktyvdinskoe				
Mezhdurechenskoe				
Pruptskoe				
Aikinskoe				
Zheleznodorozhnoe				
General operation mode (favorable ecosystem state)				
Storozhevskoe				
Sysolskoe				
Udorskoe				
	Unfavorable ecosystem state, reduction of stability			
	Slight increase in stability			
	Significant increase in stability			
	Maximum increase in ecosystem stability			

Source: own analysis.

a long management period. This assessment is presented for forestries in two formats: a matrix with color coding of the certain services types' state of and a cartogram, reflecting the territorial differentiation of the ecosystem's favorability and the exploitation mode corresponding to its state. A summary of trends in biodiversity and ecosystem functions considered during the study period: conservation or extinction of rare species, water regulation (increase/decrease in groundwater flow), water protection (accumulation of surface runoff) and carbon sequestration is presented in *Table 3*.

Analysis of all ecosystem services, taking into account the activation or weakening of functions, allowed us to designate favorable and unfavorable areas (forestries) in the zone of active forest management. Based on the ratio of positive and negative trends in ecosystem functions, in-depth differentiation of the state and grouping of forestries by the nature of restrictions and the recommended exploitation mode, taking into account the necessary conservation measures and reduction of anthropogenic load, was carried out. The matrix of forestries' ecosystems state is visualized on the cartogram (*Fig. 5*).

Figure 5. Differentiation of forestries by ecosystem state over the 2000–2020 study period and proposed exploitation mode



Source: own analysis.

A situation in which an ecosystem is subjected to strong pressures that have resulted in a decrease in resilience across the three ecosystem services, characterizes an unfavorable ecosystem state. At the same time, a particularly strict exploitation mode with maximum reduction of felling is recommended. This situation has developed on the territory of Priluzskoe, Kazhimskoe and Pechora-Ilychskoe forestries.

The predominant part of the active forest management zone is classified as an area of favorable ecological state, where we suggested general, restricted and strict exploitation modes.

The strict exploitation mode is recommended in forestries, where one or two eco-system functions have reduced stability. This is either a decrease in water storage in surface or underground horizons, or a decrease in carbon sequestration by forests, or a loss of habitat for rare species of flora and fauna. Such a mode includes mandatory logging activities in accordance with forest certification, installation of information boards of the water protection zone of small rivers and increased attention of nature protection authorities. This situation is typical for the following forestries: Pomozdinskoe, Lokchimskoe, Komsomolskoe, Letskoe, Koigorodskoe, Syktyvkarskoe, Ertomskoe and Kortkerosskoe.

The exploitation mode with restrictions corresponds to an ecosystem state where there is no weakening of ecosystem functions, but the ecosystem is in a borderline state of initial or intermediate level of perceived negative impacts. On the territory of Syktyvdinskoe, Pruptskoe, Ust-Kulomskoe, Ust-Nemskoe, Mezhdurechenskoe, Zheleznodorozhnoe, Meshchurskoe, Chernamskoe, Aikinskoe, Troitsko-Pechorskoe forestries there is an increase in carbon sequestration and water storage in underground and surface horizons; preservation of rare species of animals and fish, and habitats of vascular plants. However, there are signs of a borderline state here – a slight increase in stability prevails in the state characteristics, which dictates anthropogenic constraints, particularly in logging.

The general exploitation mode with fulfillment of all regulatory obligations is recommended in an area where a favorable situation is ensured by maximum increase in the sustainability of several ecosystem functions. These forestries are inherently stable, meaning that the ecosystem copes with actual or past (characteristic of Udorskoe forestry) loads, or the actual load does not exceed the capacity of the system. On the territory of Storozhevskoe, Udorskoe and Sysolskoe forestries the habitats of valuable fish and animals have been preserved. Due to the increase in forest area, surface water runoff in rivers has been accumulated; the level of carbon sequestration is high. We should also note that these areas are characterized by a high proportion of intact forests (Udorskoe forestry) and objects of integrated environmental protection (Kortkerosskoe forestry).

Qualitative analysis of the situation was limited by the incomplete information base of forest characteristics (bonitet and completeness for all age categories of coniferous and deciduous species), and also by the short period of observation (2008–2020), during which there was no transition of forest plantations to another age category, which requires at least 20–25 years. Nevertheless, many indicators had a sufficient period of observation (2000–2020) and reflect an adequate situation of the ongoing impact on the natural environment.

Conclusion

The accounting of ecosystem functions in the assessment of the state of natural capital of the region's intensive forest management area in the dynamics of twenty years is pioneering. The assessment of biodiversity and regulating services reflected the following positions of their state:

– logging activities during the study period did not result in a significant decline in the known populations of rare species;

– transportation network that facilitates access to natural resources has not had a significant impact due to its low density;

– decrease in the number of valuable fish is observed in the basins of the Mezen, Vychegda rivers and its tributaries due to poaching and reduction of river flow in small watercourses caused by intensive logging;

– groundwater runoff accumulation occurs on the territory of most forestries; no significant deterioration of surface runoff accumulation is observed despite logging operations and reduction of water availability in small tributaries of the main rivers;

– water protection of small watercourses is among the socio-ecological responsibilities of loggers;

– practically the entire area of active forest management has a strong carbon sequestration capacity, and during the study period this capacity was not only preserved, but also increased.

In general, we can state the relative stability of the state of ecosystem services within the forestry territories over the period 2000–2020. Despite relatively comfortable natural conditions, the territories of a number of forestries in the southern part of the region are subject to exploitation pressure that may hinder the restoration of forest ecosystems. As a result of intensive logging, there may be threats of biodiversity decline, weakening of groundwater flow accumulation and surface runoff accumulation functions.

The use of this algorithm for ecosystem condition assessment can be applied to large logging companies, large areas of logging leases in different Russian regions. The data obtained can contribute to the planning elements of the optimal list of environmental measures. Taking into account the accumulated foreign experience, prospective studies may be related to the valuation of ecological services to analyze the possibility of compensation for nature restoration in relation to large loggers in the region.

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