Pol. J. Environ. Stud. Vol. 32, No. 6 (2023), 5619-5630
DOI: *10.15244/pjoes/169403* ONLINE PUBLICATION DATE: 2023-10-30

Original Research

Effect of Forests Stands of Rudny Altai (Eastern Kazakhstan) on the Formation of Snow Cover

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Received: 10 January 2023
Accepted: 8 July 2023

Abstract

The results of snow measurements in Rudny Altai during 2020-2022 are analyzed. The influence of meteorological factors on the formation of snow cover in stands of various species composition is considered. Studies have shown that temporal aspect of changes in the characteristics of the snow cover is associated primarily with the weather conditions of a particular season. Precipitation in the winter season of 2020- 2021 fell by 62 mm less than in 2021-2022 and in the bushy area in 2022, moisture reserves were 16% more than in 2021. In a birch stand, this difference was 33%, and in a fir stand - 48%. Against the background of zonal-climatic patterns of snow cover formation, local factors that determine the spatial distribution of snow, its depth, density, dates of formation and melting, and duration of duration of existence have a great influence. In this regard, the differences in the formation of snow cover in various phytocenoses, which are represented in the mountain conditions of the Rudny Altai, are very significant. The data obtained show that the birch and fir forests practically did not differ in the water content in the snow at the end of March 2022 (408 and 410 mm), while in the area with shrubs, water content in the snow was 44-46 mm lower than in the fir forest. The results of field studies will make it possible to scientifically substantiate the basic principles of forest management within the boundaries of catchment areas based on the basin approach. Data received expand existing ideas on the hydrological role of mountain forests; they can be included in a common database and used to build a universal model that reflects the dependence of coefficient water content in snow on a number of trees stand characteristics and climatic conditions that affect the formation of snow cover in the forest.

Keywords: Rudny Altai, snow cover, formation, characteristics, forests stands

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Introduction

Snow cover is an important factor in the functioning of ecosystems, especially in areas, where it has a long occurrence. As a climate product, snow cover determines many indicators of ecosystems: changing their hydrothermal regime, influencing soil-forming processes, plant and animal life. Snow prevents deep-freezing of the soil and death of plants [1-4]. With a snow cover depth of 15-50 cm, the difference in air temperature on the surface and under the snow reaches 15-20ºC, while it is the greater, the looser the snow. Snow is a reliable thermal protection for plants and numerous representatives of forest fauna wintering in the soil. When logging, it contributes to the preservation of small undergrowth. The conditions for the life of organisms under the snow depend on the depth and density of the snow. Seasonal dynamics and the nature of snow cover affect the availability of winter food for most forest animals and birds; determines the possibility of their movement in the thickness of the snow and the characteristics of migrations of ungulates.

The more important significance of snow as a physical substance lies in the fact, that it is the most meaningful source of water resources in Northern Eurasia, North America, Central Asia and other regions. For Rudny Altai, the territory of which is the part of the Irtysh River catchment area, the problem of the safety of water resources is very relevant. The importance of monitoring and assessing the variability of snow reserves in river basins can hardly be overestimated, given their practical significance and the climate changes observed in recent decades. A sharp rise in river runoff during the snowmelt period, which determines its annual anomalies, sets the task of forecasting spring runoff in order to prevent the negative consequences of anomalous water rise, and take into account the water supply necessary for the development and environmental safety of large regions [5].

In areas with a long-term snow cover, forest ecosystems are one of the major components, which control snow reserves at watersheds, and so regulate river runoff. Influence of forest vegetation on snowfall is evident in snow pack differences between under forest canopy and open sites. Vegetation impacts snow cover distribution within individual forest stands, which distribution, in turn, controls the horizontal variability of the amount of snow moisture penetrated under forest canopy and has great ecological importance [6]. On upwind-forested slopes, blizzard-induced under-canopy snow transfer occurs, which process is known to be a key factor accounting for snow cover distribution and snow moisture balance changes [7, 8].

The discussion of this problem in hydrological literature [9-13] shows that forest vegetation has a complex influence on snow cover development and this issue should be approached with an account of zonal and regional characteristics of snow cover as an environmental factor. Snow pack differences induced by elevation, regional characteristics, and topographic conditions, which, in fact, determine precipitation amounts, are often much more pronounced and can smooth out or even completely obscure those induced by vegetation cover patterns [14, 15].

In the last two or three decades, there has been a trend towards a reduction in publications related to ground-based studies and the appearance of works reflecting the results of remote observations [16-19]. This reflects the actual situation in the development of methods for studying snow cover. Recognizing the promise of remote sense methods in large-scale studies, one should take into account the experience of ground truth data, which is far from being fully formalized in the form of specific models and GIS technologies.

The purpose of this work was to assess the hydrological role of the Rudny Altai forests on the results of our own field studies (ground truth). During the research, the following tasks were solved: to identify the features of the influence of primary and secondary forests on the formation of snow cover and on the process of snowmelt, taking into account the meteorological conditions of specific winter seasons.

Material and Methods

Study Area

Research was carried out in the basin of the Zhuravlikha River, a tributary of the Ulba River, located at Rudny Altai. Rudny Altai is part of the Altai mountain system, which includes the Tigiretsky, Ulbinsky, Ivanovsky, Ubinsky and other ranges. The eastern parts of the ranges are strongly dissected and have an alpine character. To the west, the mountains go down, their forms become rounded, and the slopes are gentle. In some places, there are plateaus with leveled surfaces. In accordance with the geographical zoning of the Kazakhstan Altai [20], the study area belongs to the Uba-Ulba low-mountain sub region of the northern low-mountain-mid-mountain forest region of fir forests, where low-mountain relief prevails with absolute elevations of 600-1000 m.

The climate is sharply continental, with large daily and annual air temperature amplitudes. The absolute minimum temperature is minus 52ºC; the maximum temperature is plus 46ºC. The spatial distribution of precipitation is uneven. In highland areas over 1000-1500 mm, at the foot of the mountains 400-500 mm. In winter, there is a lot of snow in the mountains. Sometimes its thickness reaches 3 meters. The duration of the growing season is from 110 to 130 days.

A persistent snow cover, according to the data of the Ridder hydro meteorological station, falls on the ground in mid-October and lasts for about 170 days. In some years, this happens in December or even in January. In study area snow cover is destroyed in a shorter time than it is established. According to long-term average estimates, this happens on March 27, which is associated with a rapid increase in air temperature in the spring months, although sometimes the destruction of a snow cover can occur only in May [21].

Due to the heterogeneity of orography and climatic conditions, the vegetation cover of the Rudny Altai is highly diverse and is subject to both latitudinal and vertical zonality. The entire range of vegetation zones characteristic of the mountain systems of Northern Eurasia is represented in the Rudny Altai Mountains.

According to forest zoning [22], the mountain forests of the region are identified as a special region - the southwestern sub area of fir forests of the Western Altai forest-growing province (Rudny Altai). The spatial heterogeneity of the forest cover of Rudny Altai makes it possible to divide its territory into forest regions and sub regions [20].

The main forest-forming species in the region is Siberian fir (Abies sibirica Ledeb.). Dark coniferous forests in the mountains of southern Siberia are distinguished as a separate type of forest vegetation - chern taiga. Birch (Betula pendula Roth.) and aspen (*Populus tremula* L.) are also present in these forests.

The monitoring plots, where the studies are carried out are represented by the most representative phytocenoses in this region: birch, aspen, fir stands and shrub associations. Research objects are located on the territory of the Zhuravlikha forest enterprise of the municipal state institution "Ridder Forestry". The studied phytocenoses are located in close proximity to each other and grow within the catchment area of the Zhuravlikha River on the slopes of the western exposure with a steepness of 15-20°. (Fig. 1). The geographic coordinates of the sites are as follows: № 1 - birch plantation (50°27'19"N: 83°30'20"E); № 2 - aspen plantation (50°26'47"N: 83°30'26"E); № 3 - fir plantation (50°27'01"N: 83°30'21"E); № 4 - bushy area (50°26'55"N: 83°30'19"E). Inventory characteristics of plant communities are given in Table 1.

Field Measurements

The investigations of snow cover dynamics were conducted during 2020-2022 years at four monitoring objects, located at the right bank Ulba River - western macroslope of the Uba Ridge.

The formation and melting of snow cover were studied on specially equipped stationary plots with three permanent snow gauges installed on them. Observations were carried out from the moment of forming a persistent snow cover, until its complete disappearance in the spring [23]. Permanent snow gauges were installed on the plots, forming an equilateral triangle, with a distance of 15 m between them. Each lath was assigned a number (No. 1, No. 2, No. 3). The relative positions of the laths and their numbering were preserved throughout the observations. We measured snow depths and weighed snow in situ during the period of highest-snow cover water equivalent (March 1-20), shortly before the beginning of snow melt. We did 20-30 depth measurement replicates on each sample plot and three times at each point.

Data Processing

To determine the density of snow, a weight snow measure instrument was used. The density of snow was determined from the ratio of the mass of snow to its volume:

$$d = m / V \tag{1}$$

were d – kg/m³; m is the mass of snow, kg; V is the volume of snow, m

The volume of the snow sample is calculated by the formula:

$$V = \pi \times r^2 \times h = s \times h \tag{2}$$

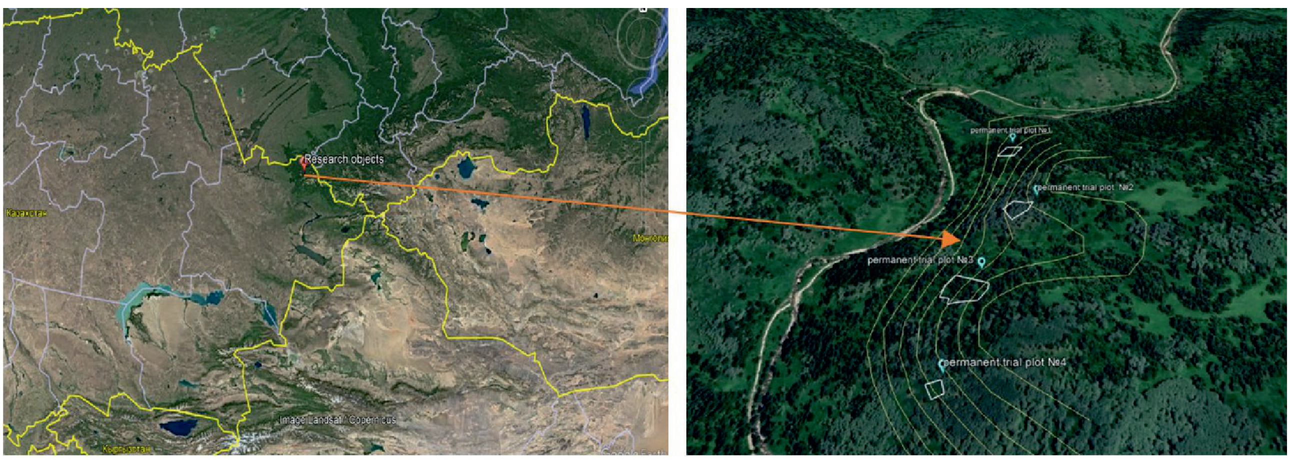

Fig. 1. Location of research objects.

Table 1. Forest inventory indicators of forest stands at monitoring plots.

Species composition	Age. years	Mean		Sum of tree cross-sectional areas. m²/ha	Forest stand quality	Stock. m³/ha	Completeness of the forest stand
		Height. m	Diameter. cm				
Plot 1 - birch forest stand							
10B	B41	15.6	14.9	24.18	I	180	1.09
Plot 2 - aspen forest stand							
10A+B	A 60	229	22.0	27.11	I	281	0.81
	B 59	21.6	27.3	1.51	I	15	0.05
Plot 3 - fir forest stand							
8F2B	F 80	17.3	20.7	16.57	III	135	0.72
	B 80	18.0	36.8	4.15	III	35	0.17
Plot 4 - shrub plant community							
8Ac2Sp	Ac	15	2.0	2	V		0.5
	Sp	15	1.0	2			

F – fir. B– birch. A – aspen. Ac – acacia. Sp- spiraea

where r - is the radius of the snow gauge, cm; s - is the area of the snow gauge sample, cm², h - is the height of the snow sample, cm.

Despite the use of various models, GIS technologies, this method is widely used in hydrological studies of snow cover [24, 25].

The water reserves in the snow cover (water content in snow) were calculated using the formula:

$$a = 10 \times h \times d \tag{3}$$

where, a is the water content in snow, mm; d is the density, kg/m³; h is the height of the snow sample, cm; 10 is a multiplier for converting centimeters to millimeters.

In the result of statistical data processing, the average characteristics of snow cover and their root mean square deviations were calculated.

Results and Discussion

Seasonal Dynamics of Snow Cover

As shown by the analysis of meteorological data from the weather station Ridder, the winter seasons of 2020-2021 and 2021-2022 differed in terms of both temperature and precipitation: the average air temperature during the snow cover period in 2020-2021 was -7.4ºC, and the next year only -5.5ºC; precipitation in the winter season of 2020- 2021 fell by 62 mm less than in 2021-2022. The irregularity of solid precipitation by months was observed for both periods of observation (Fig. 2).

Analyzing the dynamics of snow cover in the temporal aspect, it should be noted, that despite the local features of snow accumulation in each monitoring site, in all test plots, the synchronism of changes in snow depth by months was followed with the accumulated amount of solid precipitation for a given period (Fig. 3a-d). Hence, the dynamics of snow cover in the temporal aspect quite well reflect the specific weather conditions in the region. Our data are in good agreement with the results of modern hydrologists [26-33], which studied seasonal dynamics of snow cover.

The interannual variation in the snow depth on the objects under study reflects the general trends in the change in the total moisture content of the region during the cold period of the year, snow depth and water content in snow of our monitoring plots correlate with the amount of solid precipitation at the Ridder weather station. The correlation coefficients for the open area was were 0.87, and for the forest areas of the study area 0.95-0.97. The decrease in snow depth observed in the diagrams during the winter months is due to snow how that were frequently observed during the winter months in 2022. Unlike the winter season 2020-2021, when the average monthly air temperatures in December and January were 3-4ºC below the long-term averages, in the winter season 2021-2022 in December the air temperature was 2.4ºC above average, and in January - by 3.3ºC.

Our data show that the average values of air temperature and precipitation for the winter season are reflected in the water content in snow. However, as Kozii states in their work [34], changing winter weather conditions significantly affect the evaporation of snow from canopies and changes in the water content in snow under tree canopies. Therefore, it is necessary to take into account climate changes on smaller time scales than the average values of air temperature and precipitation for the winter season. We compared

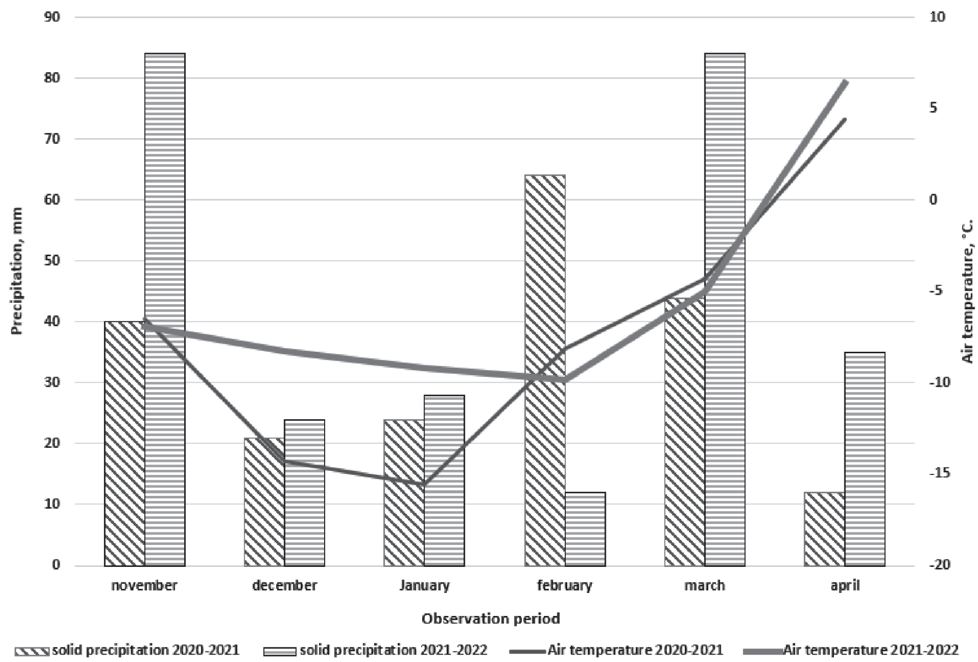

Fig. 2. Characteristics of air temperature and total precipitation for the cold period

changes in the characteristics of the temperature regime and precipitation with snow reserves over decades (Fig. 3), which more correctly reflects the relationship between changes in weather conditions and the dynamics of moisture reserves in snow.

A sharp increase in air temperature in April, which is typical for the study area, makes for to intensive snowmelt. Moreover, despite the fact that snow reserves in the early spring of 2022 exceeded those in 2021, due to higher air temperatures, snow melting in April 2022 ended 5 days earlier than in 2021.

The Variability of Snow Cover Characteristics at Monitoring Sites

If climatic factors determine the background values of snow cover, then at the local level, the peculiarities of the vegetation cover largely affects the duration of snow cover and water content in snow. Analyzing the data on the height of the snow cover at monitoring sites (Figs 4-5), showed that the maximum values of the characters are typical for birch stands. This is consistent with the results of many researchers who have studied the formation of snow cover in deciduous forest stands [35-38].

The rather high value of the snow depth in the fir forest at the end of March 2022 is obviously associated with the shedding of snow from the fir crowns after heavy snowfalls. The maximum snow depths at the beginning of March 2021 in an open area with shrub vegetation are due to significant snowfalls at the end of February (the snow was still loose, i.e. it had not had time to compact). Already after 10 days in this plot, a decrease in the height of snow begins with an increase in its density.

As the results of our field studies carried out during the period of maximum snow storage have shown, that the features of snow accumulation depends on the type of vegetation. In an open area overgrown with shrubs and in a birch forest, a uniform distribution of snow cover was noted, deviations from the arithmetic mean of the snow height along the entire profile, both in the shrub community and in the birch forest, did not exceed 15-20 cm. The fir forest is characterized by an extremely uneven distribution of snow, associated with the shedding of snow from the crowns and the formation of near-stem snowdrifts and the accumulation of snow in the gaps (small patches) between the trees. As shown by the mapping of territories at monitoring plots, the influence of the micro relief on the uneven occurrence of snow is excluded.

The difference between extreme values of the snow cover height along the profile in the fir forest range from 60 to 75 cm. The deviations of the values from the arithmetic mean range from 2 to 43 cm (Fig. 6, A-B) for both 2021 and 2022. This indicates that the variability of snow depth is determined not by the amount of snowfall, but by the density of crowns.

The density of snow, despite the dependence on meteorological factors and the duration of the snow cover, is a good indicator characterizing the effect of forest vegetation on snow. Snow depth is a relatively simple quantity to measure when visual observation from snow gauges is sufficient. While density requires more complex and costly procedures [26, 39]. According to Pistocchi [26], the density of snow is a fairly conservative value, usually limited during the snow season to between 200 and 400 kg/m^3. He also states that snow density tends to increase faster in spring than in early winter.

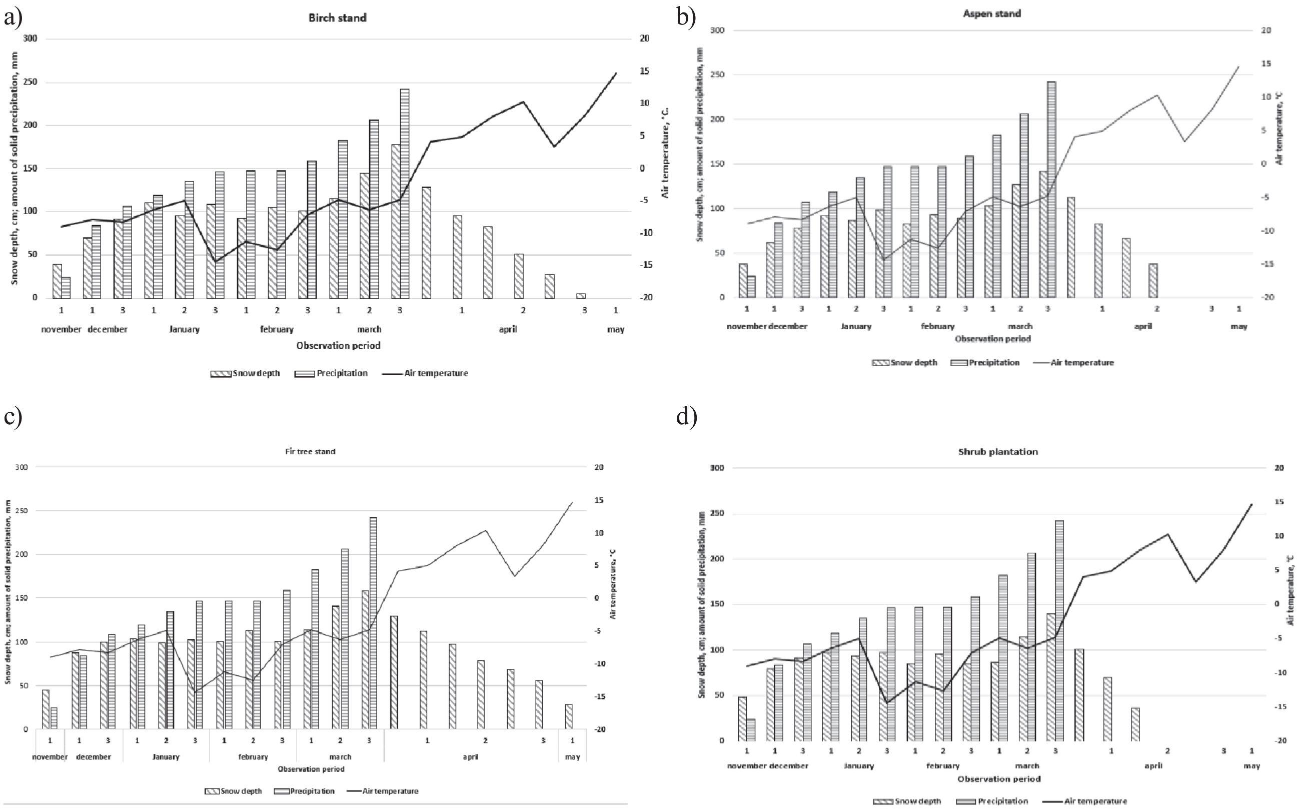

Fig. 3.(a-d) Change in snow depth and accumulated precipitation by decades (1-3) at the Ridder meteorological station (data of 2022 year).

In the plots 1-3 snow density during the winter months equals 220-250 кg/m³ and increases only during snowmelt, while in the open area (plot 4) it is characterized by constant fluctuations from 270 to 370 kg/m³ associated with thaws and the influence of wind. The relationship between changes in snow density and air temperature is shown in Fig. 7. A comparison of this indicator for the study phytocenoses shows that the effect of forest vegetation levels out the influence of solar radiation and wind on snow density, which in turn affects other characteristics of the snow cover.

Snow-Accumulating Properties of Forest Stands

Observations of snow cover on stationary rails show individual bursts of snow reserves at monitoring plots in different periods of the winter season. More often, this is due to heavy snowfalls and is temporary. Frequent snowfalls contribute to maximum snow accumulation, which is reflected in snowmelt and groundwater recharge. The balance of snow moisture, accumulated during the winter period, determines the assessment of the hydrological role of forests.

From this point of view, it is important to know how much snow moisture will be available to form surface runoff and recharge groundwater. As a rule, to solve this problem, data obtained as a result of snow measuring before snow melting are used, which already take into account evaporation from the snow surface and moisture loss during the evaporation of precipitation intercepted by tree crowns (Fig. 8).

As a criterion for assessing snow accumulation in forests, relative values are used, the so-called snow water content in snow coefficient or snow accumulation coefficient, which are the ratio of water content in snow at the forest to water content in snow at small forest glade or in deciduous forest stands. These coefficients characterize the snow storage capacity of forest stands and at the same time make it possible to evaluate the amount of solid atmospheric precipitation intercepted by the forest canopy.

According to the data obtained, the maximum snow reserves in 2021 differed slightly for monitoring objects, the differences between them were within the measurement error. A rather high amount of snow reserves in an open area compared to forest areas, it would seem, contradicts the generally accepted concept of the snow-accumulating role of forests. Nevertheless, a number of authors indicate that, depending on local conditions, the forest can accumulate more or less snow than open areas [6, 40-44]. Noting that the area with shrubs is in homogeneous conditions with the rest of the sample plots (height of the terrain, exposure and steepness of the slope, we are inclined to believe that weather conditions, in particular the high frequency of westerly winds, contributed to the transfer of snow along the slope, and shrubs were as buffer when holding snow.

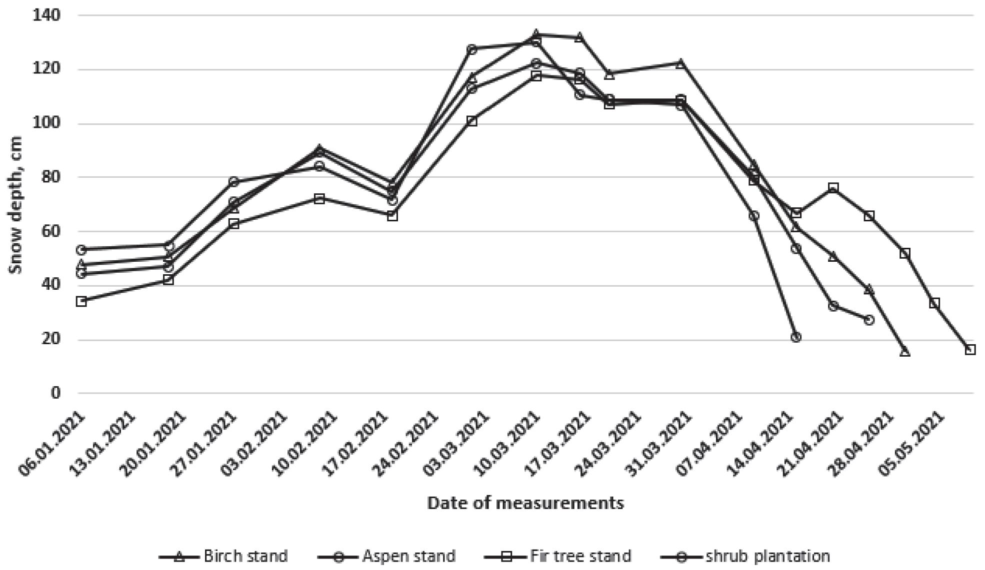

Fig. 4. Dynamics of snow cover height at monitoring plots in the winter period of 2020-2021 (according to the dates of measurements).

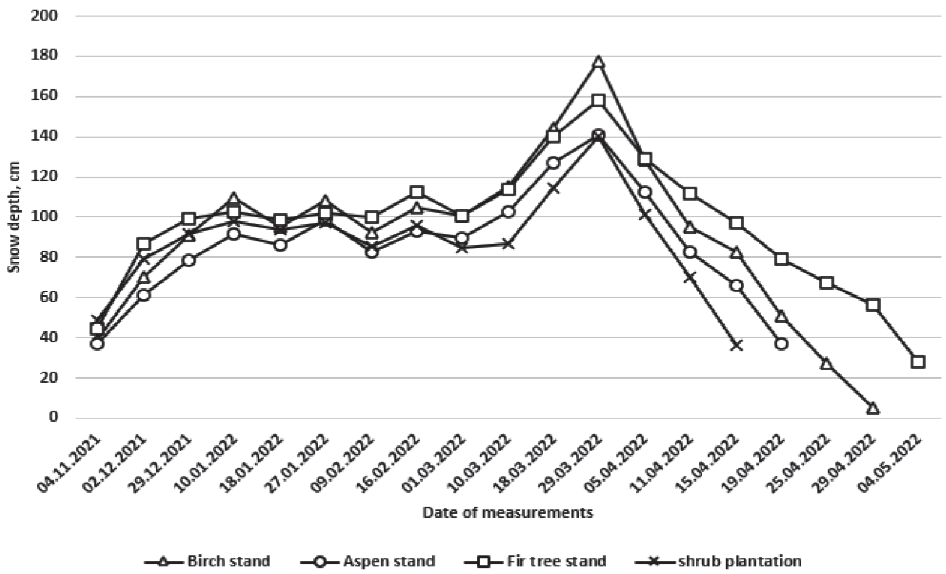

Fig. 5. Dynamics of snow cover height at monitoring plots in the winter period 2021-2022 (according to the dates of measurements).

An interesting fact is that in the winter season of 2021-2022, a completely different picture was obtained. The data obtained show that the birch and fir forests practically did not differ in the water content in the snow at the end of March 2022 (408 and 410 mm), while in the area with shrubs, water content in the snow was 44-46 mm lower than in the fir forest. These contradictory data once again confirm the role of meteorological factors in the manifestation of snow accumulation functions of forest stands. In the result of 30 years of observations, N. Kozii et al. [34] notes that about 50% of situations with snow accumulation in plantations were determined by weather conditions.

The authors of this paper agree with the opinion of researchers [44, 45] that the best snow-accumulating properties are characteristic of forest stands in which tree crowns do not form a continuous canopy that prevents snow from falling to the ground. Such properties characterize deciduous forest, as well as any stands with a large number of open areas in the forest. According to the results of the ground truth data, the fir forest is a clump-type stands with open areas and slight crown density. Due to the peculiarities of the structure of the forest cover, this plantation can be considered as a snow moisture accumulator, which is practically not inferior to deciduous forest stands.

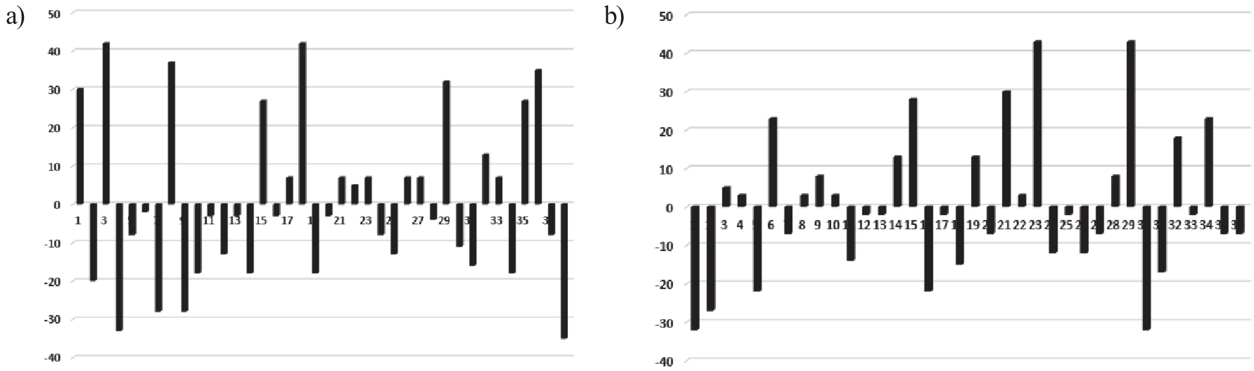

Fig. 6. Deviations of the snow depth on the profile in the fir forest from the arithmetic mean value; a) March 2021; b) March 2022 (1, 2, 3 ... – measurement points).

Assessment of the Snow-Accumulating Role of Study Phytocenoses

For a more objective assessment of the snow-accumulating role of this fir forest stands, we used the coefficient of water content in snow. As shown by two-year studies, this indicator for birch and aspen plantations was 0.92-0.95, which is quite consistent with the literature data for many regions of Northern Eurasia. In the fir forest, the coefficient of water content in snow on the day of the snow measurements in 2021 was 0.71, and in 2022 – 0.81. This indicates that the snow-accumulating role of fir forest stands largely depends on weather conditions and the amount of precipitation. As noted above, in the winter period of 2021-2022, 60 mm more solid precipitation was recorded at the Ridder weather station than in the winter season of 2020-2021. In addition, this year was characterized by thaws. Rare but heavy snowfalls in this winter season increased the penetration of solid atmospheric precipitation under the forest canopy, and thaws with the transition of air temperatures above zero contributed to the snow sliding from the branches, replenishing snow reserves under the forest canopy.

According to the coefficient of water content in snow, it is possible to evaluate the loss of unproductive moisture by this phytocenosis for the evaporation of solid precipitation intercepted by the crowns of trees. Taking into account that the interception of precipitation by tree crowns, and, accordingly, snow reserves depend

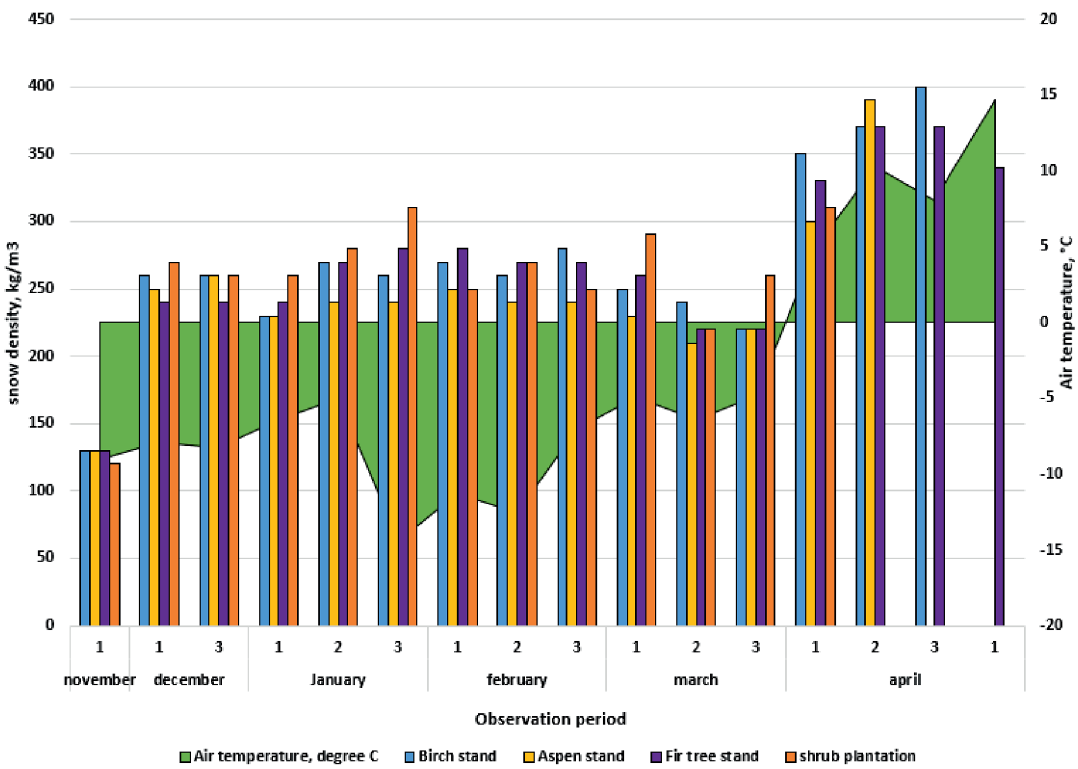

Fig. 7. Change in snow density in the studied phytocenoses depending on air temperature.

a)

b)

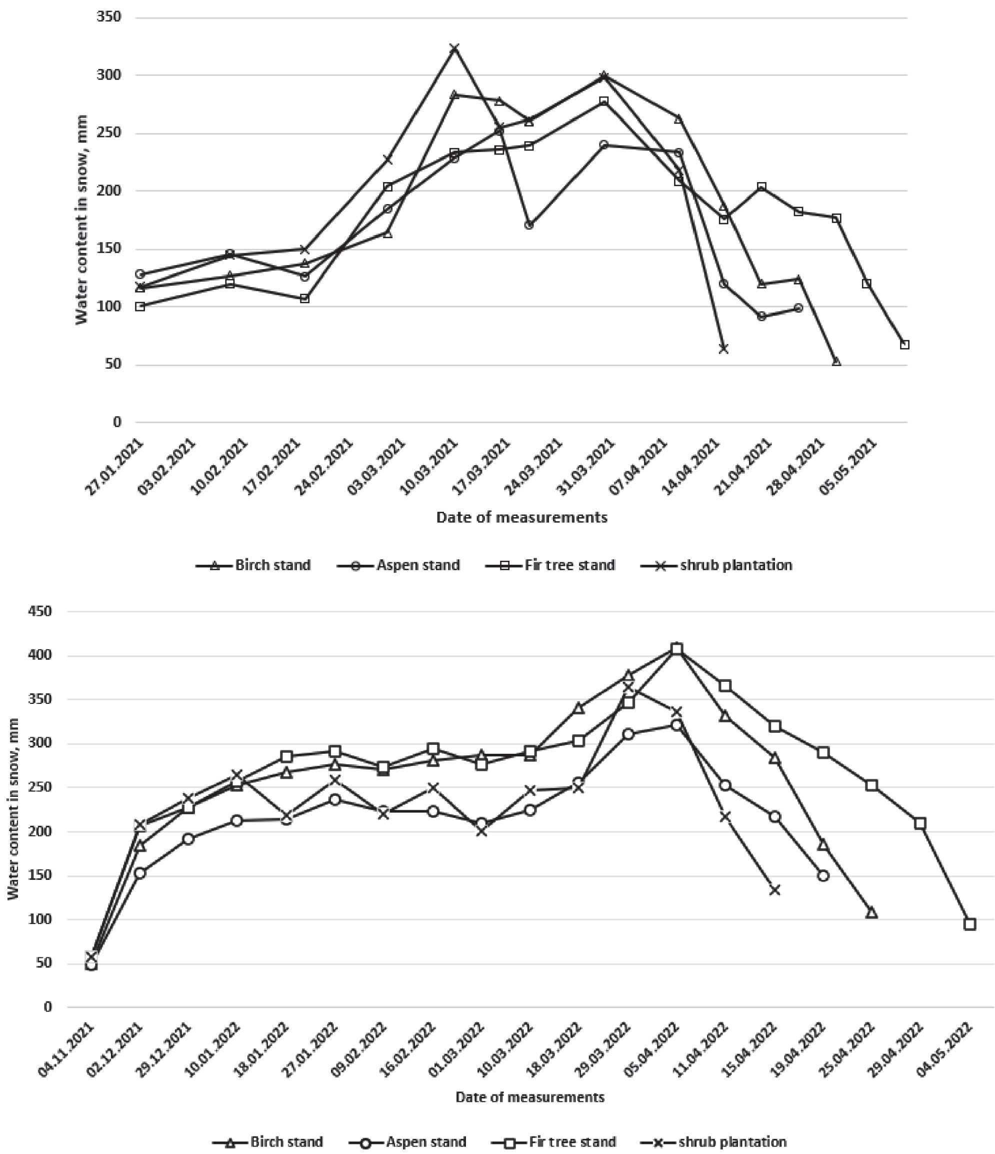

Fig. 8. Dynamics of water content in snow at the studied objects for 2020-2021 a) and 2021-2022 b) winter seasons.

on not only taxation characteristics of forest stands, but also on the weather and climatic conditions of the region, we calculated coefficient of water content in snow for our monitoring plot at the fir forest for march of 2021 and 2022 years. We used the model (1) obtained by A.A. Onuchin [11] for coniferous forests of Northern Eurasia:

$$K = 115{,}0 + 0{,}026S0 - \left(\frac{13{,}0lnA}{lnT}\right) - 1{,}5L \times \mathrm{C} - 2{,}3X \times \mathrm{C} - 6{,}6E \times \mathrm{C} - 1{,}9\mathrm{B} \quad (4)$$

$$R^2 = 0{,}73;\ G = 9{,}1;\ F = 208{,}3$$

Where: K – coefficient of water content in snow, %; So – background water content in snow, mm; T is the absolute value of the average monthly air temperature in January, [ºC]; A is the average age of the forest stand, years; L is the number of larch units in the forest stand; X is the total number of conifers, with the exception of larch and Tien Shan spruce; E is the number of Tien Shan spruce units in the forest stand; C – canopy closeness; B – indicator of bonitet (for I, II, III, etc. bonitet classes, the values were taken equal to 1, 2, 3, etc. respectively) R^2 – coefficient of determination; G is the standard error in determining the snow storage coefficient, %; F – Fisher criterion.

The values of the calculated coefficients of water content in snow for the fir forest were 0,86 in 2021 and 0,84 in 2022. The figures obtained are somewhat overestimated compared to the actual data and do not show differences for the two observation periods under consideration. This is quite understandable, because the models are the result of generalization of data for a very large region and do not take into account the local features of the territories that can affect the formation of snow cover. At the level of river watersheds of various levels, excluding streams and shallow watercourses, the model can be used to assess the snow-accumulating properties of various forest stands.

In general, assessing the snow-accumulating role of the considered phytocenoses, the most prevailing in the forest zone of the Rudny Altai, it can be noted that most of the snow accumulates in deciduous plantations. Despite the fact that fir crowns are able to intercept up to 30% of solid precipitation, these forest stands retain more than 80% of snow moisture.

Shrub communities affect the redistribution of snow: with increased wind activity, they keep snow from being blown away and contribute to its accumulation on slopes. This is confirmed by the relatively high values of snow reserves in the bushy area.

In terms of the water protection and water-regulating role of these forest stands, the priority undoubtedly belongs to fir forests, as evidenced by the results of observations of snowmelt. Depending on the rapid warming in spring, the timing of snowmelt varies for the seasons, but general trends appear. In the fir forest, snow melts 19-24 days later than in the shrub community. Compared to deciduous stands, snowmelt in a fir forest extends until early May, i.e. snow lies under the canopy of conifers for 9-10 days longer. This is of great importance for Rudny Altai, because all streams that form their runoff in this region are tributaries of the Irtysh. As you know, the safety of the water resources of the Irtysh River is an urgent problem at the international level, because this river belongs to the category of Transboundary Rivers.

Conclusions

Thus, the results obtained made it possible to identify differences in the influence of various phytocenoses, represented in the Rudny Altai Mountains, on the spatial distribution of snow cover and the snowmelt process. Investigation have shown that the general trend in the dynamics of snow reserves over the years is typical for all objects of study. This is determined by the interannual variability of the amount of solid precipitation and the weather conditions of specific years.

The results confirm the concept of most researchers that the role of boreal forests as a moisture cycle regulator is mainly reduced to obtaining a snow-accumulating effect. All plant communities represented in the Rudny Altai make a certain contribution to the preservation of snow moisture. However, obtained results allow to state the fact, that of all the studied phytocenoses, fir plantations satisfy the most significant water regulating and water protection role in the catchment area of the Zhuravlikha River. It is connected with snowmelt in spring. In the fir forest, snow melts 19-24 days later than in the shrub community and for 9-10 days longer then in deciduous forest. Contributing to slow snowmelt in the watershed, these forests protect the soil cover from erosion and help smooth out the flood on the river.

Our research confirmed that the effect of dark-needle forests on snowpack distribution and snow accumulation is an important research issue, because the hydrological regime of tributaries of the Irtysh depends largely on snow water balance of their catchments.

The results of studying the temporal-spatial dynamics of snow cover in the forests of Rudny Altai expand the existing understanding of the hydrological role of mountain forest ecosystems. These data can be included in a common database and used to build a universal model that reflects the dependence of snow indicators on characteristics of forest stands and climatic conditions.

Acknowledgments

This research is funded by the Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan (No. BP10263776).

Conflict of Interest

The authors declare no conflict of interest.

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