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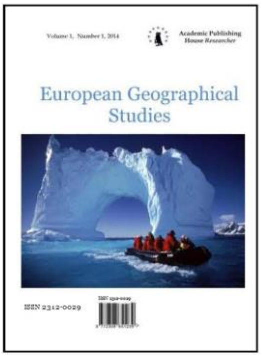

Agrarian and Forest Landscapes in Steppe: Prevention of Soil Deflation During Climate Warming

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Abstract

The analysis of the current state of agriculturally developed steppe landscapes of the Russian Federation and Kazakhstan with the indication of such environmental problems as deflation, water erosion and soil salinization is given. Using the steppe areas of Altai Krai as a case study, the peculiarities of landscape formation are discussed, and the meteorological data for the lowland part of the region are analyzed. Based on these data, a climatic trend is determined and compared with the global one. It is concluded that the regional climate changes, associated with aridization, lead to the enhancement of deflation processes. To stabilize the processes, it is proposed to use agricultural and forestry techniques. The current state of forest plantations in Altai Krai is investigated according to their functional use, species and age composition. The estimated data on the optimal areas of protective forest strips for arable land are given.

Keywords: desertification processes, Kulunda lowland, meteorological parameters, aridization, shelter forests, land protection.

1. Introduction

Western Siberia and Kazakhstan are the largest steppe zones in the world with efficient agriculture. According to the data of the Unified Interdepartmental Information and Statistical System (https://fedstat.ru) of 2016, the agricultural areas in the Russian Federation (RF) accounted for 197.7 million hectares. Currently, 65 % of arable lands, 28 % of hayfields and 50 % of pastures in Russia are exposed to the devastating effect of water and wind erosion, recurrent droughts, dry winds and dust storms (Kulick, 2009).

In 37 regions of the RF steppe landscapes occupy an area of more than 89.8 million hectares (Smelyansky, 2012). In Altai Krai, a steppe zone covers 10 596.2 thousand hectares (http://www.gks.ru); this is the largest steppe in Russia. At the same time, Altai Krai refers to the most desertification-prone areas.

The tense situation is caused by aridization of climate and agriculture intensification (Mordkovich et al., 1997). The long-term land use in the region at the end of the XX century resulted in a situation when 54.7 % of steppe agricultural landscapes were exposed to deflation, 11.6 % – to water erosion, and 19.4 % – to salinization (Burlakova, 1997).

The leading role in the preservation of land resources, increase of crop productivity, and environmental management belongs to the protective afforestation. Russia is the birthplace of field-protective forestation in the world (Kulick et al., 2015; Barabanov et al., 2017); the activities of such

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kind are extremely rare in other countries (Zhuang et al., 2017). For more than 150 years of its history, a theoretical and methodological basis for forest melioration, implemented in the form of local forest and agrarian landscapes within all agricultural regions, is developed (Kulick et al., 2015). This work is still in progress (Kulick, Popova, 2013; Chekanyshkin, Lepekhin, 2015; Manaenkov, Korneeva, 2015).

China is characterized by equally large-scale forest reclamation activities aimed at combating desertification (Guo et al., 2014; Yan et al., 2015; Zhuang et al., 2017; Jixia et al., 2018; Sun et al., 2018; Yang et al., 2018).

Here, since 1978, a 75-year (until 2050) Three-North Shelter / Protective Forest Program is being implemented (Yan et al., 2015). The authors emphasize that understanding the dynamics of desertification and its driving forces is a precondition for controlling desertification. However, there is little evidence to directly link causal effects with desertification process (i.e., on the changing area of sandy land) because desertification is a complex process, that can be affected by vegetation (including vegetation cover and extent of shelter forests) and water factors such as precipitation, surface soil moisture, and evapotranspiration (Yan et al., 2015).

The investigation's results indicate that wind has a strong promotional effect on dust weather, while forestry ecological engineering and rainfall have a containment effect. In addition, the impacts of the four studied forestry ecological engineering projects on dust weather differ. For every increase of 1000 km^2 in the Three-North Shelter Forest Project, the annual number of days of sandstorm weather decreased by 4 days. Similarly, for every increase of 1000 km^2 in the Beijing-Tianjin Sandstorm Source Project, the sand-blowing weather decreased by 4.4 days annually. In addition, the Natural Forest Protection Project and the Grain for Green Project have a more obvious inhibitory effect on the dust-floating weather (Jixia et al., 2018).

Such studies are carried out all over the world in the face of global climate change to evaluate the aridization of territories, to combat soil degradation, and in recent years, to assess the ecosystem services (Pravalie et al., 2014; Ussuri, Lal, 2017; Yakimov, 2014).

This study is aimed at the assessment of stabilization of desertification and degradation processes in steppe agricultural landscapes under the current climate change, and the development of practical recommendations for the protection of arable land of Altai Krai from deflation.

2. Materials and methods

The territory of Altai Krai represents a series of high-altitude steps elevating from the north-west to the south-east from the Kulunda lowland to the Altai mountains (see Figure 1). The flat land makes up 78 % of the region area (Table 1) and is distinguished by the developed agriculture. The relationship between heat and moisture, the number of sunny days and the total temperature of the growth season allow to grow hard wheat, which is of particular value for processing and food industries.

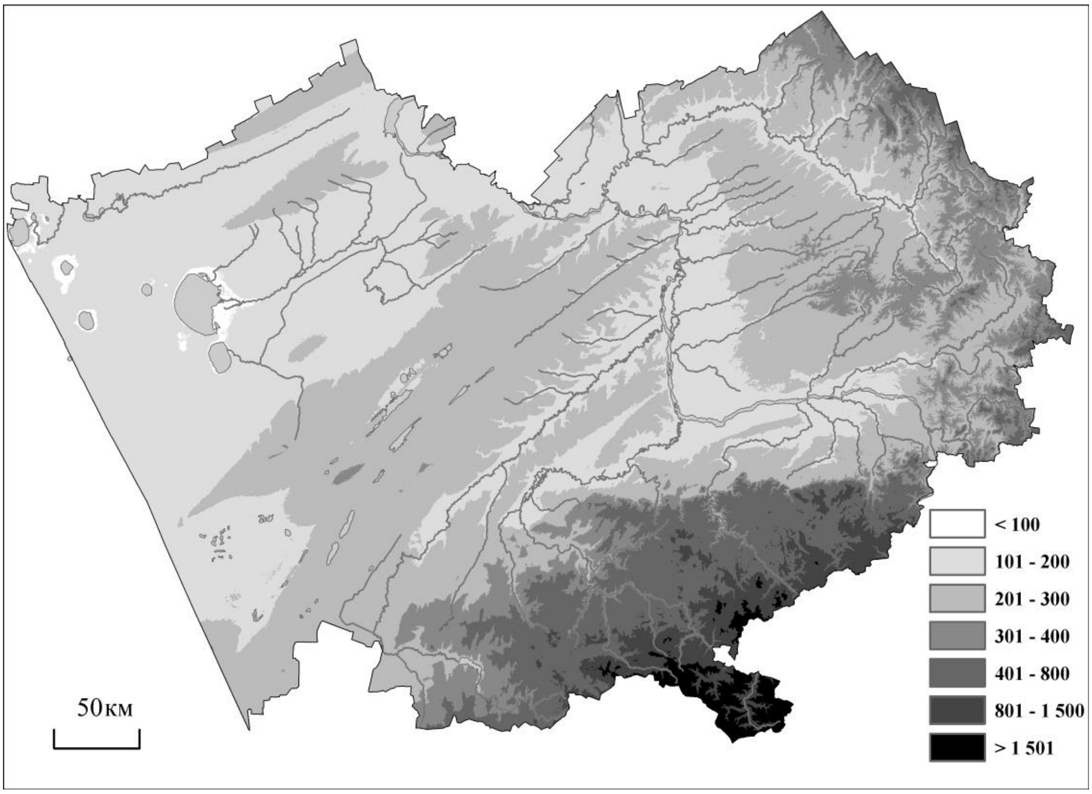

Fig. 1. Orographic schematic map of Altai Krai, m a.s.l.

The Kulunda lowland shows a very weak erosion pattern (Skripko, 2013) due to the low elevation of the territory above sea level (the Baltic Elevation System) and dry climate. This is precisely why the ploughness here reaches the maximum level: in some municipalities the arable land occupies 90–95 % of the total area (statistical data). In 1954-1956 a large-scale agricultural development of these territories took place. At that time, in accordance with the decision of the state authorities, the plowing of virgin and fallow lands in Siberia, the Urals, the Volga region, and Kazakhstan occurred. During the period from 1954 to 1960, more than 16 million hectares of land, including 2.9 million hectares in the Altai, were brought under cultivation (Pavlova, 2014).

Table 1. Altitude division of Altai Krai territory

Altitude interval, m	Area, km²	Share, %
Less than 100	2000.2	1.2
101-200	64482.0	38.3
201 – 300	65170.1	38.7
301 – 400	14807.9	8.8
401 – 800	14912.2	8.9
801 – 1500	5170.9	3.1
1501 and more	1779.8	1.0
Total:	168323.1	100.0

The plain areas of Altai Krai, found along the left bank of the Ob river, are distinguished by ribbon-like relict pine forests confined to the valleys of the ancient flow.

Melt glacial waters flowing from the Altai Mountains played a major role in the formation of the plain relief on the left bank of the Ob. During the last glaciation, they were dammed in the north by a glacier and then they moved south-westward through the hollows of old rivers (left tributaries of Ob river). At the sites of ancient waterflows, powerful sand deposits were formed. Here, pine trees (*Pínus sylvéstris*) began to grow, forming the ribbon-like relic pine forests in the South of Western Siberia.

The initial material for the study was taken from the available literature, state and regional acts on climate change, meteorological data for the plain part of Altai Krai, inventory data on shelter forests, and the authors' study of the state, growth, preservation and snow accumulation in forest strips of agricultural landscapes for the period of 2009–2014.

In recent years, remote sensing methods have become increasingly popular for studying the viability of forest strips (Yang et al., 2018). Field works on the inventory of forest strips include the reconnaissance survey and selection of the site that most fully reflects the state of the strip. The width of the test site corresponds to the width of the forest strip. The length depends on the age of the trees and the number of rows. For example, at the tree age of 20 years, the area of the test site should be not less than 0.15 hectares, over 20 years – up to 0.40 hectares.

The following works are performed at the test site with entering the data in the record card. First, shelter forests are broken down into categories (field protective, anti-erosion, gully, shore-fixing, roadside, green belts). The structure of a forest belt is marked; it can be permeable, open, and impermeable or thickly planted. The number of rows and the main wood species are established. The height of the trees is estimated using altimeters, and the trees are grouped according the age: under 20 years, 21-30, 31-40 and 41 plus. Thereafter the conservation of trees is evaluated using the following scale: under 10 %, 11-30, 31-50, 51-70 and 71 % and above. The state of the trees is estimated by a three-point scale: one point – the portion of dry twigs in the crown is less than 25 %, two points – the portion of dry twigs in the crown is up to 50 % and the crown is partially dried out, three points – the portion of dry twigs in the crown is above 50 % and a part of trees is dry.

Further, the anthropogenic impacts on the forest belt are noted. These are fire damage, unauthorized felling, soil consolidation and changes in grass cover as a result of grazing. The presence or absence of natural regeneration of the main wood species should be noted showing the approximate number per one hectare. The regrowth is determined by a three-point scale: three points – shoots are characterized by healthy growth, bright color of the leaves, and vigorous appearance; two points – satisfactory growth, with an irregular distribution around the stump; one point – poor shoot, inviable, growth is slow. Measures to strengthen the influence of the forest belt on the surrounding fields (thinning, addition of large-size planting material, partial or complete reconstruction) are noted.

The collected and processed data for 60 municipalities formed the basis of analytical materials presented to the Forest Department and the Government of Altai Krai. The data were processed with the use of statistical methods and software, including the use of GIS technologies. The data were processed with the use of statistical methods and software, including the use of GIS technologies.

Such methods and investigations to assess the land-improvement impact of forest belts, their viability and opportunity to accumulate precipitation were conducted in other agricultural regions of Russia (Tanyukevich, Zuravleva, 2015; Cheverdin et al., 2016; Timer'yanov, Rakhmatullin, 2016). We considered their experience in the field and laboratory studies, the results of which are presented in the paper.

3. Discussion

Climate aridization. Aridization is most often understood as the climate drying. However, this concept also includes the processes of soil erosion, changes in plant communities and their replacement by xerophytic (drought-resistant) species of plants etc. Therefore, in the broader sense aridization is equated to desertification of territories. These two processes coincide in time and space.

Climate change predicted for the twenty-first century, obviously, will have a significant impact on the change of borders of natural zones and landscapes (State report…, 2003, Assessment report…, 2008).

According to the analytical data for the XXI century, the average temperature of the surface air layer in Russia will increase. The greatest warming is expected in Siberia. The areas with sufficient or excessive precipitation will experience water resources enlargement. In deficit-water areas, the situation is likely to worsen resulting in serious socio-economic and environmental consequences (Assessment report…, 2008).

Currently, Altai Krai is characterized by the following thermal conditions: ***warm*** – the sum of active temperatures (ΣT >10°C) 2000-2200°C is peculiar to 40 % of the area, ***very warm*** (2200–-2400°C) – 26 % and ***moderately warm*** (1800-2200 °C) – 22 % (Mikhailova et al., 2008).

If the observed trend of climate change continues to persist over 25 years, the temperature conditions will correspond to ***hot conditions*** – for 49% of the territory, ***very warm*** – 31 % and ***warm*** – 13 %. In this case, the forest-steppe zone may be replaced by arid steppe, and the arid steppe – by dry steppe. The occurrence of desert landscapes is possible instead of dry steppe. In the mountains, this process will be reflected in change of the altitudinal vegetation line, i.e. the elevation of the tree line due to the alpine belt, which in its turn, will induce the elevation of the steppe zone due to the lower tree line, whether it is black taiga in the low mountains of North-Eastern Altai or park larch forest in the middle mountains of Central and South-Western Altai.

To represent climate changes in the region, we analyzed the data from 14 weather stations, including eight stations in the lowland part of the region and six – in the mountains. We used the average annual air temperature and precipitation, and considered the data by 10-year periods from 1961 to 2016.

In the western regions of Altai Krai (Table 2) over the past 50-60 years, the average annual temperature of the surface air layer has increased by almost 2°C at ordinary average annual precipitation. Thus, according to the data from Klyuchi weather station (dry steppe) for the study period, the average annual air temperature increased from 2.1°C to 3.6° C or by1.7 times. At the same time, the amount of precipitations decreased by 5 mm – from 273 to 268 mm, which is indicative of desertification of climate.

Similar changes take place at other observation points. For instance, in the northern regions of Altai Krai, the temperature rise reached 2.4 times, and the amount of precipitations increased by only 8-12%. Similar pattern occurs in the southern regions, however, with constant precipitation, the rise of the surface air temperature here is more intensive.

If we compare the average annual precipitation for a 10-year period to the average annual air temperature, we will get the following data. In Barnaul, in 1961-1970, precipitation was as large as 254 mm/°C, in 2001-2010 – 157 mm/°C, and in 2011-2016 – 148 mm/°C. The Klyuchi weather station showed 131 mm/°C, 73 mm/°C, and 75 mm/°C, respectively, that also confirms the intensification of climate aridization.

Table 2. Dynamics of major meteorological parameters

Weather station	Periods					
	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	2011-2016
Barnaul	1.73/441	1.65/397	2.26/412	2.78/430	2.77/436	3.03/450
Volchikha	1.42/357	1.47/334	2.29/348	2.61/323	2.83/313	2.82/316
Klyuchi	2.09/273	2.47/259	3.00/261	3.84/256	3.70/271	3.59/268
Rebrikha	1.43/415	1.43/407	2.42/395	2.08/389	2.69/371	2.66/359
Slavgorod	2.14/263	1.79/336	2.52/357	2.70/306	3.51/305	3.69/319

Note: numerator – average annual temperature over the period, °C, denominator – average annual precipitation over the period, mm.

We identified the years of high solar activity and, using the average precipitation for three years (preceding and following), we can reason, according to the data from the Klyuchi weather station over the period of 45 years, that the average annual temperature increased from 1.8 to 3.4°C and the annual precipitation grew by 9 % at constant relative humidity (Table 3). The Barnaul weather station revealed lesser increase of temperature (from 1.9 to 2.7) and precipitation (by 5 %) at the same relative humidity.

Table 3. Major meteorological data for years of solar activity

Year of solar activity	Klyuchi weather station			Barnaul weather station		
	temperature, °C	precipitation, mm	relative humidity, %	temperature, °C	precipitation, mm	relative humidity, %
1967	1.8	266	66.3	1.9	390	69.6
1978	3.6	251	65.4	2.0	443	75.0
1989	3.5	284	69.0	3.0	361	70.2
2000	3.8	295	63.9	2.9	451	72.7
2012	3.4	290	61.0	2.7	409	71.1

By this is meant that climate aridization will have an adverse impact on the state of forests, the silvicultural and valuation indicators, which will steadily decrease. Under such conditions, it is possible to regulate the response of agricultural landscapes to desertification only through the combined use of agrotechnical and forestry techniques. At the same time, deflation is one of the essential problems that should be overcome.

Stabilization of deflation processes. The aridization of climate leads to desertification and land degradation. Soil degradation refers to the processes associated with its depletion. Most often it is due to wind and water erosion. Deflation is accompanied by blowing. Destruction of soils occurs under the influence of wind. The most acute problems of deflation are in the steppe and semi-desert regions, in areas of effective agricultural development. When the favorable natural features are enhanced by anthropogenic factors, they are repeatedly accelerated. What are the ways to regulate the deflation processes in steppe? In our opinion, spring and summer precipitation play here a key role.

Moisture conditions during the warm season depend on both liquid precipitation and the solid one accumulated during the cold season. Currently, it is impossible to affect the amount of liquid precipitation, but it is possible to influence the amount of solid precipitation.

The accumulation of snow in the fields is due to a decrease in the rate of snow transfer in the surface air layer. The most effective measure is to make the surface rough, for example, with the help of snow-retaining shields. However, the occurrence of forest strips is more effective. In this case, snow is accumulated not only in the strip but also on the adjacent field, especially in the lee of the strip. The snow depth in protected fields can reach 40-50 cm as compared to the open steppe (15–20 cm). This means that in spring the amount of liquid precipitation will exceed by at least 80–100 mm (Sub-regional…, 2000, Simonenko, 2001).

Based on soil and climatic characteristics (Kukis,; Gorin, 1973), divided the territory of Altai Krai into five reclamative afforestation areas (RAA) (Figure 2): I – West-Kulunda (dry steppe), II – East Kulunda (arid steppe), III – Left-bank (relative to Ob river; semi-dry steppe with kolkis), IV – Right-bank (humid temperate forest-steppe), and V – Piedmont (meadow steppe and forest-steppe).

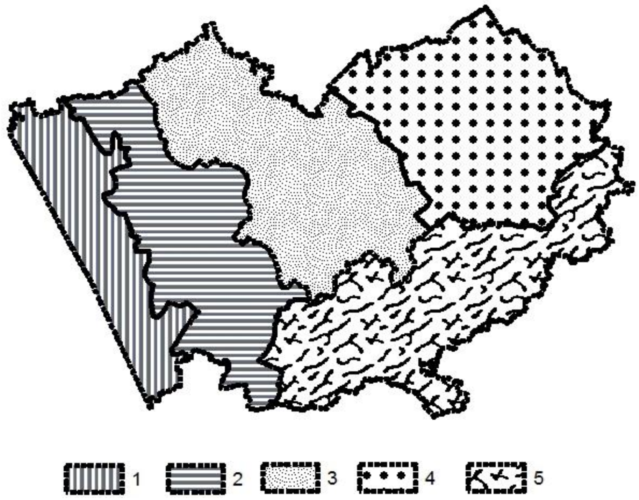

Fig. 2. Scheme of reclamative afforestation division in Altai Krai

For 80 years, from 1937 to 2017, about 206 thousand hectares of shelter forests (SF) appeared in the region, of which 79.4 thousand hectares are found currently; they represent 0.75 % of agricultural area or 1.2 % of the arable land in the region. The vast majority of forest strips (90.7 %) refer by their functional use to the field-protective strips (Tables 4, 5). Another 3.0 % perform the conservation function, and 4.7 % are the roadside strips. The rest 1.6 % include the coastal plantations, and urban green belts.

Table 4. Characteristics of shelter forests in Altai Krai, th. ha %

RAA	SF, total	including:			
		Field-protective	Anti-erosion	Roadside	Other
I	23991.7	21999.8	731.4	860.8	399.7
	100.0	91.7	2.9	3.7	1.7
II	26851.6	24502.5	998.7	819.5	530.8
	100.0	91.3	3.7	3.0	2.0
III	17835.2	16539.6	319.2	809.4	167.1
	100.0	92.7	1.6	4.5	1.2
IV	7324.3	6333.5	354.7	598.2	37.9
	100.0	86.5	4.8	8.2	0.5
V	3271.4	2589.9	30.7	610.6	40.2
	100.0	79.2	0.9	18.7	1.2
Total	79353.9	72007.7	2435.4	3735.1	1175.7
	100.0	90.7	3.0	4.7	1.6

Table 5. Species composition of shelter forests in Altai Krai, th. ha %

RAA	SF,total	Species composition			
		Birch	Poplar	Maple	Other
I	23991.7	9356.5	5486.9	3823.0	3333.3
	100.0	42.7	25.0	17.3	15.0
II	26851.6	8410.5	10407.6	2764.7	2919.7
	100.0	34.3	42.5	11.3	11.5
III	17835.2	5212.6	10069.8	900.7	350.9
	100.0	31.5	61.2	5.4	0.9
IV	7324.3	367.2	5688.8	146.3	132.1
	100.0	5.8	89.8	2.3	2.1

V	3271.4	294.4	2077.3	156.6	61.6
	100.0	11.3	80.2	6.1	2.4
Total	79353.9	23653.8	33745.1	7795.3	6809.0
	100.0	32.9	46.8	10.8	9.5

The species composition of forest strips is as follows: the silver birch occupies the area of 23.6 thousand hectares (32.9 %), balsam poplar – 33.7 thousand hectares (46.8 %), ash-leaved maple – 7.8 thousand hectares (10,8 %), softwood (Scotch pine and Siberian larch) – 0.4 thousand ha; other hardy-shrub species cover 9.5 % of the SF area.

It should be noted that coniferous trees were poorly introduced into protective afforestation due to weak growth during the first years. The analysis shows that at the age of 30, their height is practically the same as that of birch and poplar. Besides, the coniferous trees are more viable.

The forest strips occupying the area of 7.8 thousand hectares, where the ash-leaved maple dominated, eventually became impassable and windproof facilitated the larger snow accumulation in the immediate vicinity. The same is true for the forest strips, where the ash-leaved maples grow under the crown cover of the main wood species. In 2011, these strips covered the area of 9.0 thousand hectares.

The age structure of forest strips conforms with the periods of their planting. The share of forest belts under the age of 20 is about 0.3 %, aged from 21 to 30 years – 2.2 %, from 31 to 49 years – 39.9 %, and over 41 – 57.6 %. A great bulk of forest vegetation has reached its critical age. The field protection functioning of birch and poplar in steppe does not exceed 45 years (Simonenko, 2001).

The rapid degradation of forest belts is caused by both biological and anthropogenic factors. If the biological factors are associated with the environment adverse for wood species, the anthropogenic impact results from forest fires, unauthorized felling of forests, cattle grazing.

It should be noted that over the next 10 years, a half of the forest stand aged over 40 years and covering more than 41.5 thousand hectares will die and the area of strips will reduce to 50.0 thousand hectares. By 2025, the area of forest strips in the region may reduce to 30-35 thousand hectares.

In agricultural afforestation, the main index for forest strips is the height, on which the area of the protected field depends. The most quick-growing tree species in the region is balsam poplar, the height of which at the age of 30-35 reaches 15.3 m as compared to birch and maple (13.1 and 5.9, respectively).

As regards the snow retention, the strips made up of two or three rows of trees are the most effective (Table 6). Usually, the strips are permeable and promote a more uniform distribution of snow within the space between them. Besides, they are self-sufficient in spring water due to small hips of snow in the strip. Particularly, it is peculiar to pine and larch forest strips. Such forest strip ensures the accumulation of 30-40 cm thick snow and taking into account the accumulation of snow at the edge of the strip – up to 50 cm, which corresponds to 120–150 mm of liquid precipitation. That is, the amount of precipitation on the protected field increases by 60–80 mm.

Table 6. Snow accumulation in three-row strips of different wood species

RAA	Wood species	Space between strips, m	Average snow depth, cm	Amount of water, mm	Share of water from snow,%
I	Poplar	300	28.1	78.8	30.0
	Birch	300	24.6	68.9	26.3
II	Poplar	300	32.0	90.0	22.2
	Poplar	200	38.4	107.5	26.5

There is no significant difference in snow accumulation in the strips of different wood species and the space between the strips. However, the strip of balsam poplar accumulates the larger quantity of snow than that of European white elm due to the difference in the height (poplar – 9–10 m, elm – 6–7 m).

Based on the data from Klyuchi weather station over the past 50-60 years, we found that in some years the April-June period distinguished by much more liquid and solid precipitation than the average long-term dynamics (80 mm). Such a one-two year excess, as a rule, alternates with two- or three-year dry periods (Figure 3). This is evidenced by the dynamics of precipitation in the twentieth century. Currently, the situation has changed even more towards the aridization of climate, and the periods with precipitation less than 80 mm have become longer (three-four years).

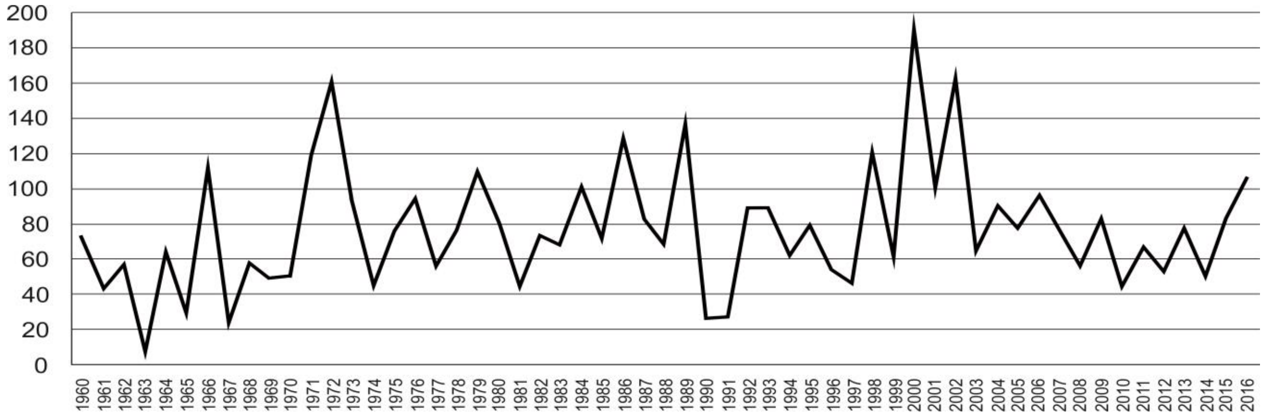

Fig. 3. Dynamics of total precipitation for April-June period, mm

In the general cycle of aridization over the recent years, the precipitation of 2005–2015 is similar to the values of 1960–1970. Most likely, after the wet and hence high-yield period of 2016–2017, when the grain crop in the region was as high as 4.5-5.2 million tons, a three-four-year period with precipitation less than 80 mm (April–June) is expected. Therefore, the issue of the size of area necessary for effective field protection is of crucial importance.

The forestry practice considers optimal the ratio, when one hectare of forest strip protects 25–30 hectares of arable land in the dry steppe, 40–45 hectares – in arid steppe, and 50–60 hectares – in the forest-steppe. In other words, the share of forest stand in dry and arid steppes should be 4–5 % of the area of agricultural land.

According to our calculations, the deflation of soil in dry steppe can be prevented by 31–33 thousand hectares of shelter forests (currently they occupy 24 th. ha), in the arid steppe – 40–42 th. ha (26.8 th. ha), and the forest-steppe and foothill steppes – 70–73 th. ha. Hence, to regulate the desertification, there should be 140-150 thousand hectares of protective forest plantations (Table 7).

Furthermore, forest reclamation contributes to the improvement of the hydrothermal regime of soils and more than four times reduction of land runoff. Protective forests, being a part of agrarian and forest landscapes in the steppe, serve as the basis for landscape specific agriculture. Owing to forest strips, the average yield of grain crops increases by 18-23 %, industrial – by 20-26 %, and green crops – by 29-31 %.

Table 7. Optimal area of shelter forests for arable land protection

RAA	Arable land, th. ha	Share of arable land, %	Tree and shrubbery vegetation, th. ha	Share of SF, th. ha	Optimal area of SF,th. ha	Lack of SF with regard to replacement, th. ha	Arable land covered by forests,%
I	1513.6	64.6	30.5	19.8	38.3	22.0	7.1
II	2251.1	69.0	58.3	75.9	47.5	25.6	5.0
III	7729.6	69.1	89.2	19.4	50.2	32.5	4.0
IV	2407.2	60.0	49.4	6.4	25.0	19.3	3.1
V	1936.9	39.4	71.8	2.8	13.2	10.5	3.0
Total	10848.4	61.1	299.2	74.3	174.2	109.9	4.2

4. Conclusion

1. The current state of steppe afforestation in Altai Krai does not meet the requirements for regulation of soil degradation. The current aridization of climate and desertification of steppe areas contribute largely to the deterioration of agrarian and forest landscapes.

2. To improve the state of agrarian and forest landscapes, it is necessary to develop projects on the establishment of shelter belts within steppe and forest-steppe zones of Altai Krai, including the Kulunda area. Besides, it is essential to determine the legal status of shelter belts, to appeal to landowners to take care of the existing shelter belts as well as to establish the new ones.

3. Considering the climate change in steppe zone during the recent years, the sustainable agrarian management including soil conservation can be achieved by a twofold increase of shelter forests.

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