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FIRES IN ARID AGROFORESTAL LANDSCAPES AND THEIR DAMAGE ASSESSMENT

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ABSTRACT

Impact of shelter forest belts of *Robinia pseudoacacia L.* on spread of fires and the damage caused by them was investigated in arid agroforestal landscapes of Russia. A mathematical model for arid regions of the world was obtained. According to the model, the area of fires in agrarian lands in habitats with forest shelter belts of the 1st class life-state varies by an average of 1.22 ha/hour comparing to plantations of the 2nd and 3rd classes – up to 1.56 ha/hour. The forest belts could suffer low (a forest stand is not substantially damaged), medium (more than 10% of live trees) and severe (less than 10% of live trees) degree of damages by fire. The damage caused in this case amounts to US$ 220, 853 and 2,210 / ha. The world community has been recommended a method for fighting fires in arid agroforestal landscapes "Don Fire Protection" developed at the Don State Agrarian University. A new scientific direction "agroforestry pyrology" is substantiated; agroforestal landscapes exposed to wildfires is its research object and the main task is to study the patterns of occurrence, behaviour and consequences of fires on forest-meliorated lands in order to develop fire-safe technology of protective afforestation under global climate warming.

Key words: agroforestal landscape; fire; shelterbelt planting; damage assessment; agroforestry pyrology.

INTRODUCTION

One of the global climate aridization consequences is the deterioration of fire conditions at the most valuable categories of lands used by man for agricultural production and food security, namely, agricultural land (FAO/UHO 2007). As a rule, they are combined with forest plantations that protect agricultural land from affecting by arid climate conditions. Such landscapes in the Russian scientific literature received the name of agroforestal.

In 2017, one of the largest landscape fires named Thomas occurred in the Ventura District (California, USA) which is characterized by climate aridization in recent decades. The fire area was 270 thousand acres. Damage was estimated at US$ 34 million. According to the official data of the Global Fire Monitoring Center (GFMC) and the UN Office for Disaster Risk Reduction (UNISDR), the landscape fire problem in climate aridization conditions is relevant for agrarian regions of France, Portugal and Croatia, arid subregions of Asia, Africa and South America (DUBENOK *et al.* 2017; Headquarters of Russian Emergency Situations Ministry in the Rostov region, 2018). In Australia, the largest wildfires occurred in 2003, 2005, 2007, especially large with an area of 430 thousand hectares in February 2009 against the background of air temperature +43 °C and wind speeds of up to 30 m/s. In Botswana, the most dangerous was the 2008 Janzie fire over an area of over 3.5 million hectares and a total loss for the economy of US$ 250,000. The worst drought of 2007 provoked a powerful seven day landscape fire in Greece with an area of more than 270 thousand hectares, 84 people have died. Regular wildfires occur in Israel, Indonesia, Mongolia, Canada, the frequency of which correlates with dry years (ERISOV *et al*. 2016).

A similar problem is characteristic for arid agricultural regions of Russia with its extensive agroforestal landscapes. The largest fires were recorded in 1998 and 2010. The number of fires exceeded 32 thousand, the total area covered by fire was more than 2 million hectares; the damage to the economy was estimated at 100 billion rubles (ERISOV *et al*. 2016). Rostov region, the most important food region of Russia, suffers from fire most. The area of arable land here exceeds 8.8 million hectares. To combat desertification processes and to improve the productivity of agricultural land, shelterbelt plantings have been created there with total area of over 125 ha, preferably of *Robinia pseudoacacia L*., providing protective afforestation of arable land in the range of 1.92% – 3.28% (DUBENOK *et al*. 2017).

According to official data of the EMERCOM of Russia in the Rostov region, in 2016 the area of landscape fires in the region was 1320 hectares, in 2015 - 1048 hectares, in 2014 - 1895 hectares. A significant part of the fires in the region is recorded in the areas where the steppe rivers flow, especially in their bends (Headquarters of Russian Emergency Situations Ministry in the Rostov region, 2018). This is due to the active agricultural use of such lands.

Along with the well-known economic (damage to dwellings, destruction of cultivated vegetation) and environmental consequences, a fire leads to a decrease in land-reclamation and environmental protection efficiency of shelter forest belts (DUBENOK *et al*. 2017).

The general features of landscape fires in arid conditions are considered in detail in literature (ERISOV *et al*. 2016; SIDARENKO 2014; KIRILLOV, EGOROVA 2012; KOBEC 2017; TEDIM *et al*. 2015; PATON *et al*. 2015; MCGEE *et al*. 2015; SOTO *et al*. 2015; BUERGELT, SMITH 2015; SAGALA *et al*. 2015; CHEN, CHEN 2015; SCHMERBECK, KRAUS 2015; PONOMAREV *et al*. 2015; GROOT *et al*. 2015); however, the features of fire spreading over agricultural lands crossed by shelter forest belts, as well as the assessment of damage to such plantations require additional research.

The working hypothesis was that, being a biophysical boundary, the narrow shelterbelt plantings are capable either to restrain the spread of wildfires, or to speed up this process depending on their life-state.

The purpose of the studies conducted in the Rostov region of Russia in 2012–2018 was to develop a mathematical model characterizing the dynamics of fires in agroforestal landscapes of arid regions that could be applied in other regions of the world with similar climatic conditions, and also to clarify the principles for assessing damage caused by fire, and to recommend to the world community a low-cost and effective technology to combat this natural disaster.

RESEARCH METHODS

An original method was developed to achieve the research goals. The climatic conditions of the region were analysed according to the long-term data of the meteorological station of Rostov-on-Don city.

Fire danger classes (FDCs) were established in July-August depending on weather conditions in accordance with the scale approved by the order of the Federal Forestry Agency dated July 5, 2011, No. 287. The speed of fire spreading in agroforestal landscapes was determined during their extinguishing.

Pyrogenic damage to shelterbelt plantings was assessed according to the adapted classification of burned-out forests (DUBENOK *et al*. 2017):

a) Fire-damaged forest belts with the number of viable trees no more than 10% - severely damaged stands;

b) Forest belts where more than 10% of the vital trees are preserved - medium-damaged stands;

c) Plantings where the stand has been fully preserved or a single dying of the trees has occurred - low damaged stands.

In accordance with the generally accepted methodology, there were laid out 5 sample plots in each severe-, medium- and low- damaged fire stands, respectively, in typical robinian fire-damaged forest belts of the region. The enumeration survey on sample plots was carried out according to the generally accepted method, with the determination of the stock of trees damaged by fire.

Taxation indicators for the treated forest belts before the fires were established according to the inventory data of reclamative afforestations maintained by LLC Research and Production Center "Kadastr". State classes of the forest belts were assessed according to the scale by P.V. KUDRYASHOV *et al*. (1985).

To take into account the aboveground phytomass in forest belts damaged to different extents during a month after the fire, model trees were selected along the conditional cross section line in each row, the mass of which was divided into 3 fractions (barky trunks, branches, and green mass); the dry matter content was established using the thermoscales method in the laboratory. The obtained values were compared with previously published data on the phytomass of forest belts that were not exposed to fires in the region, determining the amount of burnt plant mass (DUBENOK *et al*. 2017).

In assessing damage by tree plantations, the order by the Rosleskhoz dated April 3, 1998, No. 53 and the Order of the Rostov Region Government dated April 26, 2012 No. 316 were followed. The damage caused by the decrease in the environment-forming functions of forest belts was calculated as the product of damage from wood loss by the coefficient of ecological significance of plantations (2.0). Assessing the damage to the environment due to pollution caused by forest belt burning products, the Decree of the Government of the Russian Federation dated September 13, 2016 No. 913 was applied, as well as the coefficient determined by the ecological situation and the significance of the atmospheric air condition for the Rostov region — 1.6 (approved by the Ministry of Natural Resources of the Russian Federation on November 27, 1992). Calculations were carried out in US $ in 2019 prices.

RESULTS AND DISCUSSION

The geographical area under the study was located within the Rostov region and covered the Don-Donetsk plain, the eastern part of the North Priazovskaya plain (up to the north coast of the Taganrog Bay), the eastern and southern branches of the Donetsk Ridge, the north-western part of the Kuban-Priazovskaya lowland, the Lower Don terraced accumulative lowland, as well as the space between the Don-Salsky watershed and the valley of the river Manych. This region is characterized by hot European climate-type summer (average air temperature is +23 ° C), with prevailing clear weather (sunshine duration 907 hours, total solar radiation 2017 MJ/m^2), with a precipitation amount of about 152 mm/year and dry hot east winds with speeds of 5–6 m/s. This causes a high risk of occurrence of medium and strong intensity grass fires in agroforestal landscapes. A similar problem is noted in other arid regions of the world (KOBEC 2017; TEDIM *et al*. 2015; PATON *et al*. 2015; MCGEE *et al*. 2015; SOTO *et al*. 2015; BUERGELT, SMITH 2015; SAGALA *et al*. 2015; CHEN, CHEN 2015; SCHMERBECK, KRAUS 2015; PONOMAREV *et al*. 2015; GROOT *et al*. 2015).

The main part of afforestation belts (72%) in agroforestal landscapes of the region under study is formed by *Robinia pseudoacacia L*. These are mainly wind-managing plantings of dense structure, III quality class, I - III classes of state on a scale (KUDRYASHOV *et al*. 1985), created according to the technology generally accepted for the steppe zone of Russia.

Wildfires occurred on inarable lands and agricultural fields in July and August. The main combustible materials on farmlands are dead stands of rhizomatous vegetation (*Elytrigia repens* L.), and crop residues. The fires occurred in the period from 12.00 to 18.00 Moscow time, with FDC = III and the prevailing east wind speed of 5–6 m/s. The cause of ignition is arid climate, careless handling of fire, agricultural machinery and vehicles operation. The average fire area was 2.7 ha. The fire front spread at a speed of 1–3 m/min in a westerly direction, entering the shelterbelt plantings.

The analysis of forest inventory materials, as well as our own research (DUBENOK *et al*. 2017) allowed us to establish the average taxation indicators of black locust wind-managing forest belts in the area under study before their damage by landscape wildfires: the forest belt routes are located in the north-south direction; their composition is 10 Rb; planting height 10.5 ± 0.2 m; stem diameter 11.0 ± 0.2 cm; timber stock 64.0 ± 0.8 m^3/ha; the 4-th age class, stocking 1.0; the structure is dense; number of rows is 4; width 12 m; average area is 2.17 ha; state classes are I–III.

It has been established that in forest belts of the 1st state class (inventory numbers 25, 26, 28, 30, 36), with more than 75% share of healthy trees in the stand, the fire propagation speed decreased 2 times (less than 1 m/min) compared to open areas of agricultural land.

In afforestation belts of II state class (inventory number 8, 24, 50, 51, 54; share of dry trees in plantations is 25–49%), landscape wildfires spread out at about the same speed as in open agricultural lands (2–3 m/min).

In the shelterbelt locust plantations of the third state class (inventory numbers 1, 3, 18, 20, 23; share of healthy trees in forest belts before the fire is less than 50%)) the wildfire propagation speed increased almost 2 times (up to 6–7 m/min) compared to agricultural lands.

Regression analysis of data by process parameters of wildfire propagation in arid agroforestal landscapes allowed us to obtain a multiple regression equation that describes the relationship between the fire affected area and fire duration, as well as the state class of the afforestation belts:

$$S_{wfa} = -2616{,}54 + 67{,}85 \cdot T + 1670{,}14 \cdot K \quad at\, R = 0.933 \tag{1}$$

Where S_{wfa} - wildfire area in agroforestal landscapes, m^2; T - the landscape wildfire duration, minutes; K - the state class of belts afforestation; R is the multiple correlation coefficient. The use of multiple relationship (1) is limited by the following conditions typical for arid regions of the world: protective forest cover of arable land is 1.92 - 3.28%; FDC = III, wind speed is 5–6 m/s.

It results from Equation (1) that if all other things being equal, in agroforestal landscapes with I class state shelterbelt planting, the area of steppe fires increases, on average, by 1.22 ha / hour; and if forest belts of II–III classes are available - from 1.40 to 1.56 hectares / hour, respectively.

This fire behavior pattern can be commented on as follows. Wildfires are localized within the shelterbelt plantings of I life state class. This is due to the fact that there is practically no wood fuel in the form of deadwood and dead trees in such forest belts. The stand canopy of closed healthy plantations transmits little light to the soil, what prevents the penetration of additional combustible material into the forest belts: the steppe grassy vegetation which is dry by mid-summer. Earlier, we noted that such plantings effectively restrain the wind flow (DUBENOK *et al*. 2017), what also prevents the spreading of fire in the forest belts themselves. After a landscape wildfire, the forest stand is vital, without signs of significant pyrogenic damage that makes it possible to assess the forest belts as poorly damaged.

Forest belts of II state class do not significantly affect the speed of the wind flow, what we mentioned earlier in our publication (DUBENOK *et al*. 2017), and the amount of combustible material compared to plantations of I state class is higher here: there are dry tree vegetation and low-productive live ground cover from steppe grasses, and also litter fall. It marked the transit of wildfire through robin forest belts here. There are more than 10% of living trees after pyrogenic damage here; living ground cover is burnt almost completely. This allows evaluating these stands as moderately damaged.

Slagging in forest belts of III state class with dry and weak trees and a burning temperature of about 708 °C, active overgrowth of the undergrowth by rhizomatous and root-weeping weeds, severe wind permeability of such plantations which we described earlier (DUBENOK *et al*. 2017) contribute to an increase in the spread rate of wildfires in agroforestal landscapes. A surface fire quickly passes through such plantings to agricultural lands adjacent to them from the leeward side: fields with crop residues and inarable lands with steppe grass vegetation. There are less than 10% of living trees in these plantations after fires; live ground cover burns out. Such forest belts were rated by us as severely damaged.

The dependence presented above is consistent with the general features of fires in agroforestal landscapes of the Volgograd Region and some other regions of Russia described by KIRILLOV and EGOROVA (2012). This indicates the correctness of the mathematical model proposed by us that describes the fire behavior in arid agroforestal landscapes in multi-factorial fashion. The above equation (1) theoretically justifies the feasibility of reconstructing pure compositions in shelterbelt planting of the class II and higher in order to reduce fire danger in agroforestal landscapes with arid climate. In addition, the model can be used to predict the development of this type of fire, which will help in a timely manner to evacuate the population and make rational use of the forces and means to extinguish and localize wildfires.

Earlier, in pyrology such regression dependence by the area calculation was not used, but only a set of equations by Amosov were used (SIDARENKO 2014) describing the fire propagation speed (m / min) along the front (Vfr), the wings (V_w) and rear (V_{rear}) in a forest conditions:

$$V_{fr} = a_0 + (a_1 - a_2 y)x - a_3 y \quad (2)$$

$$V_w = 0.35\ V_{fr} + 0,17 \quad (3)$$

$$V_{rear} = 0.10\ V_{fr} + 0.20 \quad (4)$$

Where a_0, a_1, a_2, and a_3 are constant coefficients established for certain types of forests; y is the moisture content of combustible material, %; x - wind speed, m/s.

The main disadvantage of these equations is the impossibility of their application in agroforestal landscapes characterized by intersection of open territory (agricultural fields) with biophysical boundaries, namely the narrow shelterbelt planting which, as shown earlier, significantly affects wind speed in inter-belt fields. At the same time, the moisture content of the combustible material (mainly aboveground phytomass of trees) applied in formula (2), is related to the life state of plants and is taken into account in formula (1) (DUBENOK *et al*. 2017).

The following indicators necessary for an objective assessment of the damage caused by wildfires to arid agroforestal landscapes can be proposed: the extent of damage to forest belts that we have previously proposed (low, medium, severe); wood stock of dead trees; burnt aboveground phytomass; the amount of pollutant emissions into the atmosphere. The total application of these parameters in economic calculations will allow us to take into account both direct economic losses from wood loss and indirect environmental losses associated with the burning of phytomass and release of toxic substances into the atmosphere, as indicated by the work of other authors (ERISOV *et al*. 2016; SIDARENKO 2014; PONOMAREV *et al*. 2015; GROOT *et al*. 2015). An example of the corresponding calculation is presented in table 1.

Tab. 1 An example of the calculation of damage caused by wildfires in arid agroforestal landscapes.

The degree of damage to forest belts by landscape fires	Timber stock of dead trees, m^3/ha		Burnt ground phytomass, t/ha	The amount of emissions of pollutants into the atmosphere, t/ha
	Small-size workable wood	Fuel wood		
Low	4.05	1.71	1.4	0.225
Medium	15.75	6.65	5.3	0.853
Severe	40.95	17.29	11.0	1,771

As a rule, small-size workable wood accounts for 70% of the stock, and fuel wood takes 30%. Taking into account the charge rates, US$ 9.47 / m^3 and US$ 5.11 / m^3, respectively, the data in Table 1, it was possible to calculate that, under arid conditions, the damage from landscape wildfires for one hectare of poorly damaged shelterbelt planting will amount to US$ 72.06. With average and severe damage to forest belts by fire, the damage from wood loss is estimated at US$ 280.23 / ha and US$ 728.59 / ha, respectively.

The most significant is the damage from the reduction of the environment-forming functions of shelterbelt plantings. So, in the case of severe damage by a landscape fire to one afforestation belt hectare, the amount of this damage can reach US$ 1,457.18. Accordingly, with a moderate degree of damage, this figure will reach US$ 560.46 / ha, and no more than US$ 144.12 / ha for a low one.

Taking into account the amount of pollutants released into the atmosphere when 1 ton of aboveground phytomass is burnt (Table 1), the rates for emission charges (carbon dioxide - 0.02 US$/ton; hydrocarbons - 0.16 US$/ton; nitrogen oxides, suspended particles – 1.42 US$/t), and the coefficient which takes into account the environmental situation ratio for Russian North Caucasus (1.6), we were able to establish that the damage caused by emissions from the forest belts to the atmospheric air is estimated from US$ 3.34 / ha (low damage by fires) up to US$ 24.98 / ha (forest belts heavily damaged by fire). One hectare of shelterbelt planting moderately damaged by fire causes environmental damage in the amount of no more than US$ 12.22.

With a high degree of damage to the forest shelter belts, the total damage from fires may exceed US$ 2,210 / ha. This amount correlates with the cost of a complete reconstruction of such fire-damaged forest plantations in the Rostov region. With a low degree of damage to forest belts by fire, the total damage is less significant and is no more than US$ 220 / ha, what correlates with the cost of environmental harvesting.

The features of wildfires in agroforestal landscapes, as well as the results of fire damage assessment described in this paper, allow us to recommend the Don Fire Protection System (DONOZ) originally developed in Don State Agrarian University for fire monitoring, prediction, preparedness, prevention and control purposes on agricultural lands in the arid climate conditions (SHILER, SIDARENKO 2001).

The fire prevention system "DonOZ" includes:

- Early detection of fires during the fire hazardous period by using ground patrols, aviation and space monitoring measures;
- Use the irrigation network, and irrigation and drainage equipment located on agricultural lands when fire extinguishing;
- Organization of temporary spills of small rivers or streams on fire hazardous areas with the help of taphoons.

The advantage of the DonOZ system recommended is the possibility of using sprinklers, irrigation pipelines, and mobile pumping stations for fire-fighting purposes of domestic and foreign manufacture. According to the developers, the use of this set of measures capable of providing the systematic moistening of land with a norm of 30–50 m^3/ha during fire-hazardous periods, makes it possible to create powerful fire barriers around important economic facilities and settlements.

Thus, we can say that fire development processes on agroforestal landscapes are unique. In addition to climatic conditions, they depend on a number of parameters inherent only in these areas: the technology of creation and width of forest belts, their species composition, life state, taxation indicators, phytoproductiveness of stand and ground living cover, structure and protective forest cover of agricultural lands, as well as agricultural background of adjacent farmlands.

This allows us to justify the new scientific direction at the junction of agroforestry and pyrology: agroforestry pyrology. The object of research in this case will be agroforestal landscapes exposed to wildfires. The main objectives of the research are the study of the patterns of fire occurrence and behavior, and their economic impacts on the forest-meliorated lands of arid regions of the world. The practical result of research within the framework of our proposed research area may be the development of fire-safe technologies for protective afforestation in regions of the world with an arid climate.

CONCLUSION

The paper substantiates a new scientific direction: agroforestry pyrology, which studies the nature of fires in conditions of agroforestal landscapes, assesses damage caused by fire, and also develops technologies for fire-safe protective afforestation in regions of the world with arid climate.

The mathematical dependence of the wildfire area in agroforestal landscapes on its duration and the state class of the afforestation belts is obtained. It can be used to predict the fire development on agricultural lands in arid regions of the world with the aim of rational use of fire-fighting forces and means, making decisions about evacuation of the population.

It was established that the damage from the timber loss by forest belts accounted for 33%, and the losses from environmental damage and reduction in environmental protection functions accounted for 67% of the total losses caused by wildfire to agroforestal landscapes.

The world community has been recommended to use the Russian “Don Fire Protection” system for the prevention and suppression of wildfires in agroforestal landscapes under conditions of climate aridization. It is low-cost and at the same time effective in use, as it is built on application of irrigation and drainage equipment available on farmlands for fire-fighting purposes.

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