Influence of anthropogenic impact of vehicles on roadside forest plantations

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Abstract. The article presents studies of the growth and development of forest stands along highways as a result of man-made impacts from road transport emissions. The obtained mathematical model describing the dynamics of the growth of the biomass of stands of various bonities of roadside stands during the period of light saturation is presented. In this regard, the obtained mathematical model describing the dynamics of the growth of the biomass of stands of various bonities of roadside forest stands during the period of light saturation is presented. The use of the bonus in research to characterize the growth rate of forest roadside plantings depending on the distance to highways and the density of traffic flows on them allows us to characterize the amount of toxic pollutants entering forests. This allows us to assess the process of expanding the environmentally unfavorable zone along the highway. The article presents the possibility of calculating the concentration of pollutants, based on the model of turbulent diffusion, reduced, after some assumption, to the model of Gaussian distribution in atmospheric air. The dependence on the calculation of the intensity of emissions of pollutants, taking into account the composition of the traffic flow, is given.

1. Introduction

Roadside forest stands their growth and development significantly depends on the environmental conditions created by the man-made impact of road transport, the flow of which has now increased significantly on highways. This has led to simultaneous air and soil pollution, which inevitably affects the forest, stands in the roadside lane. The main technogenic pollution of the environment is the emission of combustion products in automobile engines.

The technogenic impact of road transport on the state of forest stands in the roadside lane, from the point of view of system analysis, is considered as the mutual influence of two systems that differ in the laws of development: the technical system "road transport and traffic flows" and the ecological system of roadside forest lanes. From the point of view of system analysis, there is a direct and indirect technogenic impact of the technical system "road transport and traffic flows" on the ecological state of roadside forest stands [1]:

- the direct impact consists in the removal of part of the forest ecological system for road structures with the complete destruction of the soil and vegetation cover and the change in the water regime of the soil. As a result, numerous links between the ecotope (a subsystem of inanimate nature, including the atmosphere, soil, and hydrosphere) and the biocenosis (a subsystem of living nature, including
phytocenosis, zoocenosis, and microbiocenosis) are severed.

- indirect impact on the biocenosis is carried out through the biotope through the physical and chemical impact of the flow of road transport
- physical impact in the indirect segment of the technical impact of vehicles on roadside forest stands: dust transfer from the road surface and roadsides, noise, vibration and other types of impact;
- gorenje impact is the main one in the movement of motor transport flows and is the transport by air and water of harmful and toxic substances formed as a result of chemical reactions during the combustion of hydrocarbon fuels in internal combustion engines of cars.

Thus, the technogenic impact of road transport on roadside forest stands leads to their negative state of growth and development. Conducting research on the technogenic impact of road transport on roadside forest stands will allow us to identify ways to improve the ecological state.

The experimental study and theoretical justification, assessment and forecast of the technogenic impact of road transport on the ecosystems of the roadside forest strip are actual scientific and applied tasks of the forest and automotive industries of Russia [2, 3]. The solution of these problems requires a systematic approach in experimental and theoretical studies, allows us to more accurately and scientifically substantiate the forecast of the ecological state of the roadside forest strip and develop measures to restore and preserve the stability of roadside forest ecosystems [4, 5]. The growth of motorization has now led to the need to take into account the negative impact of the emission of combustion products in car engines [6]. The purpose of this article was to determine the dependence on the influence of the technogenic impact of the emission of combustion products in motor vehicles on the bonitet of roadside forest stands. Therefore, the goal set in this article to study the impact of the technogenic impact of traffic flows on the bonitet of forest roadside plantings is relevant.

2. Materials and methods
The study was conducted in the period from 2008 to 2018 on the section of the M4 Moscow-Rostov highway no further than 100 km from the city of Voronezh (on the territory of the educational and experimental forestry Voronezh State University of Forestry and Technologies named after G F Morozov). The trial areas were located in a pine forest with a mixture of birch adjacent to the highway. As we approach the road, we can see an increase in the anthropogenic load on the forest and the degree of recreational digression of the plantings. On the adjacent forest plot there were five sections, which had the shape of an elongated rectangle of 40×60 m, oriented parallel to the highway. In these sections, the traffic intensity of road transport in both directions was about 2000 cars per hour in the daytime. On the studied roadside forest areas perpendicular to the highway at a distance of 5, 10, 15, 20 and 30 m from the road, observations were made of the effect of man-made impact of road transport on the vegetation bonitet, as well as soil samples were taken. Since it is known that with the aerosol intake of pollutants, their content in the soil drops sharply with depth, the samples were taken only from the upper mineral horizon of the soil from a depth of 30-70 (directly under the bedding) and 70-120 mm. The samples were analyzed for the pH value of the aqueous extract, the content of heavy metals of exchange cations using potentiometry, determination of calcium absorbed complexometrically (in the extract of 1 N NaCl solution), mobile sulfur on the KK-3 device (in the extract of 1 N KCl solution), chlorides ionometrically (argentometry of the aqueous extract), mobile phosphorus and potassium compounds (according to Kirsanov), as well as the gross amount of some heavy metals (neutron activation analysis). Soil samples were taken in 2012 and 2014 at a distance of 1, 5, 11, 15, 35 and 100 m (control) from the highway roadbed. In the theoretical study of bonitet roadside forest stands were used differential and integral calculus, a mathematical model that allows to analyze Roset and development spaces, depending on the energy absorbed by soil and vegetation, depending on the ecological condition of the environment.

3. Results and discussion
The impact of the technogenic impact of motor transport on roadside forest stands has not yet found its full and sufficient solution. Thus, the issues of the prevailing wood species and their optimal use in the
roadside forest zone, where the bonus varies dramatically depending on the distance of penetration into the depth of the forest products of transport pollution, have not been resolved. Thus, table 1 shows the studies conducted on the western section of the Moscow Ring Road (MKAD) (in the 8 quarter Serebryanoborskoie experimental forest Institute of forest science Russian Academy of Sciences). The trial areas are located in the exclusion zone of the road adjacent to the highway, which is occupied by pine with an admixture of birch and various grasses [7].

Table 1. Changes in the chemical parameters of the soil at different distances from the roadbed of the Moscow Ring Road (MKAD).

| Distance from MKAD, m | pH | Exchange cations, mg-eq 100 g⁻¹ | Heavy metals, mg/kg⁻¹ |
|-----------------------|----|---------------------------------|-----------------------|
|                       | pHE | Ca | Mg | Cu | Zn | Pb  |
| 1                     | 6.3 | 2.9 | 1.1 | 14 | 108 | 33  |
| 5                     | 5.9 | 2.4 | 1.2 | 14 | 90  | 29  |
| 11                    | 5.6 | 2.1 | 0.8 | 11 | 62  | 21  |
| 15                    | 5.7 | 1.3 | 0.8 | 10 | 54  | 26  |
| 35                    | 5.2 | 0.7 | 0.4 | 6  | 56  | 22  |
| Control               | 5.4 | 0.8 | 0.3 | 9  | 48  | 17  |

Roadside forest stands and the disturbance of their growth and development were studied based on the biophysical processes occurring in them. The physiology of plants, their material and energy exchange with the external environment is as follows. The chlorophyll-bearing cells of the green parts of plants absorb the light radiation of the sun and atmospheric carbon dioxide. The root system of plants provides water, nitrogen compounds and ash elements from the soil. The release of substances and energy to the external environment occurs as a result of: plant respiration; water evaporation in the processes of transpiration; with the annual shedding of leaves. As a result of the death of plants, substances and energy that once entered the plant from it return to the external environment. Thus, the requirement of plants to the environment are reduced to the presence in it of substances necessary for the exchange (e.g., soil moisture, and a minimal amount of various contaminants in soil, water and in the ambient atmosphere), as well as the required amount of energy (light, heat and thermodynamics associated with the processes of heat and mass transfer in plants). Therefore, the location of plants in the forest roadside cover is of significant importance [8-11].

At the same time, different types of forest plantations require different amounts of light energy, moisture, various substances entering the plants from the soil, react differently to the thermal regime of the soil and air, to the physical properties and composition of the soil, to its technogenic pollution, etc.

Favorable environment of plants is considered to be such in which plants are growing rapidly. As an indicator of development, the growth rate of plantings in height is usually taken, which the so-called bonitet scale determines. The better the growing conditions, the higher the height of the planting or planting will be at the same age. To determine the bonus of a particular plant, use table 2.

The bonus does not reflect the properties of the plantings, but reflects the result of the relationship between the plantings and the external environment that determines the course of plantings ' growth.

In the roadside forest zone, the moisture content of the soil is disturbed, which is to some extent reflected in the bonitet of the forest cover. A significant part of the energy in plant stands is spent on transpiration, that is, on evaporation. No less significant amount of energy is spent by plantings in the roadside forest strip on working against soil forces and on soil formation. By absorbing soil moisture in the roadside forest strip, the plant causes the movement of this moisture in the soil, its movement from the surrounding soil space to the root system of the plantings. In addition, given that in the roadside forest strip, the soil is more compacted than in the nearest forest area (filtration processes are disrupted), its water balance is disturbed, the moisture in the soil is significantly reduced, which ultimately leads to various plantings in the plantings. In addition, the bonus of forest roadside
plants is also affected by man-made soil pollution.

Table 2. The height of the plantations on bonitatem (in meters) [7].

| Age, years | I-a | I   | II  | III | IV  | V   | V-a |
|------------|-----|-----|-----|-----|-----|-----|-----|
| 10         | 6-5 | 5-4 | 4-3 | 3-2 | 2-1 | -   | -   |
| 20         | 12-10 | 9-8 | 7-6 | 6-5 | 4-3 | 2   | 1   |
| 30         | 16-14 | 13-12 | 11-10 | 9-8 | 7-6 | 5-4 | 3-2 |
| 40         | 20-18 | 17-15 | 14-13 | 12-10 | 9-8 | 7-5 | 4-3 |
| 50         | 24-21 | 20-18 | 17-15 | 14-12 | 11-9 | 8-6 | 5-4 |
| 60         | 28-24 | 23-20 | 19-17 | 16-14 | 13-11 | 10-8 | 7-5 |
| 70         | 30-26 | 25-22 | 21-19 | 18-16 | 15-12 | 11-9 | 8-6 |
| 80         | 32-28 | 27-24 | 23-21 | 20-17 | 16-14 | 13-11 | 10-7 |
| 90         | 34-30 | 29-26 | 25-23 | 22-19 | 18-15 | 14-12 | 11-8 |

Because of the conducted research, a differential equation was obtained that characterizes the various plant cover bonitets of forest roadside plantings, which determines the process of increasing the biomass of plantings over time:

\[
\frac{d\nu}{dt} = \eta \left( \frac{Q}{\eta} - \nu \right),
\]

(1)

where \(\frac{d\nu}{dt}\) – the amount of plant matter \(d\nu\) created in the plant cover during operation, that is, the increase in biomass; \(\eta\) proportionality coefficient, which determines the proportion of biomass that a given vegetation cover loses during the year; \(Q = k\lambda = \text{const}\) – constant value associated with phyto-productivity \(\gamma\); \(k\) – correction factor that takes into account the period of formation and growth of leaves, for example, for birch stands \(k = 0.7\); \(\lambda\) – absorbed light energy, called physiologically active radiation (FAR); \(\gamma\) – phyto-productivity, that is, the total amount of energy that is consumed by the vegetation cover when creating a unit of biomass.

In turn, the phyto-productivity \(\gamma\) is spent on:

a) the energy consumed for the synthesis of plant matter – it is \(21 \times 10^6\) kJ for the synthesis of 1 ton of plant matter;

b) energy expended on transpiration;

c) the energy spent on lifting soil solutions into the crowns of plantings;

d) energy spent on soil formation and work against soil forces.

Dividing the variables, equation (1) takes the form:

\[
\frac{d\nu}{Q} = \eta dt.
\]

(2)

When integrating equation (2), it should be borne in mind that it is composed for the period of maximum absorption of the headlights FAR (the period of light saturation). The amount of light energy actually absorbed, \(\lambda\), will change significantly each year as the tree cover grows [6, 12, 13]. Therefore, in the calculated dependences, instead of a constant value \((k\lambda)\), a function of time \(\lambda(t)\) will appear.

In the current research, we will take \(t\)-the moment of time at the beginning of the period of light saturation. In this case, the time of the observations carried out \(t \geq t\). Two points are considered \(t_0(t_0 \geq t)\) and \(t > t_0\). It is assumed that the moment of time \(t_0\) corresponds to the biomass \(v_0\), and the moment of time \(t\) - corresponds to the biomass \(v\). Integrating equation (2) within time \((t_0, t)\) we obtain:
\[ \int_{\frac{Q}{\eta} - \nu}^{\nu} \frac{d\nu}{\eta} = \eta \int_{t_0}^{t} dt, \quad (3) \]

or after integration:
\[ -\ln \left( \frac{Q}{\eta} - \nu \right) \bigg|_{t_0}^{\nu} = \eta(t - t_0), \quad (4) \]

after the transformation, equation (4) will take the form:
\[ \ln \left( \frac{Q}{\eta} - \nu \right) - \ln \left( \frac{Q}{\eta} - \nu_0 \right) = \eta(t - t_0), \quad (5) \]

as a result of the potentiation of equation (5), we have the form:
\[ \frac{Q - \eta \nu_0}{Q - \eta \nu} = e^{\eta(\nu - \nu_0)}, \quad (6) \]

finally, from equation (6) we obtain:
\[ \nu = \frac{Q}{\eta} - \left( \frac{Q}{\eta} - \nu_0 \right) \cdot e^{-\eta(\nu - \nu_0)}. \quad (7) \]

The resulting mathematical model equation (7) describes the dynamics of the biomass of various roadside forest plantings during the period of light saturation.

The constant \( \eta \), depending on equation (7), characterizes the speed of the process of reaching the maximum reserve of planting. The greater the \( \eta \), the faster the planting reaches its maximum reserve. In order to calculate the dependence equation (7), it is necessary to know, in addition to the used constants, \( \nu_0 \) – the value of the biomass for the initial moment of time \( t_0 \), which are determined as a result of ongoing studies for various types of forest stands in the roadside lane.

From the analysis of dependence equation (7), it follows that the bonus of roadside forest stands depends not only on the biological processes occurring in the vegetation cover, but also to a large extent on the environment, its ecological state and the energy that is used by the stands.

Thus, the conducted research on the impact of the technogenic impact of motor transport on roadside forest stands determined the need to take into account the light and heat energy of the sun, as well as the energy parameters used in the calculations of the dynamics of plant growth, which will eventually be characterized by bonitet [14-16]. However, such a task is multiparametric and complex. It is not only not solved, but actually not delivered. There are no analytical relationships between the energy consumption of the sun environment and plantings, physiological processes in plants and their transpiration and processes, heat and mass transfer. And most importantly—the impact of man-made impact of vehicles on the environmental condition in the roadside lane. The only comparison parameter in these conditions is the bonus, which can be used to judge the degree of oppression of plantings from the technogenic impact of motor transport. Such difficulties in using mathematical modeling include the following reasons:

- determination of the optimal modes of vegetation growth is insufficient, since the available mathematical models describe only the period of maximum light saturation;
- forecasting the growth of forest vegetation in roadside forest areas requires special mathematical models, taking into account not only the biological processes in plants, but also the physical processes by which these phenomena of growth and development of plants (this filtration processes in plants and soil, heat and mass transfer, thermal regimes of soils and environmental conditions of light radiation (solar energy), etc. [16-19]).

The energy that is spent on soil formation and the work of vegetation cover against soil forces in option (d) significantly prevails over the energy in options (a, b, c). It increases with the transition from the best to the worst bonuses. The total energy consumption is characterized by the parameter \( \gamma \). The relative contribution of the individual components of the energy consumed in option (d),
depending on the bonus, is also determined by the parameter $\gamma$.

As can be seen from table 3, the bonus is the most important measure of the quality of the environment. It should also be noted that part of the energy spent on overcoming soil forces and soil formation is immediately converted into heat (the soil warms up).

**Table 3.** The amount of energy spent on soil formation and work against soil forces in a pine plantation during the formation of 1 ton of organic matter, kJ/t.

| Bonitet  | 5.4·10^8 | 7.8·10^8 | 11.4·10^8 |
|----------|----------|----------|-----------|

It should be noted that the technogenic impact of road transport on roadside forest stands is determined by the amount of toxic substances emitted from the exhaust of road transport. There is pollution of the surrounding area, both the soil and the air and water environment [20-24]. This leads to a deterioration of the state of forest stands, a negative change in the chemical composition of pine needles, forest litter and soil, a decrease in the intensity of mineralization of organic matter and impoverishment of the soil. Roadside forest areas are also exposed to a number of heavy metals because of exhaust gas emissions [25-27].

In the calculations of the emission of toxic substances, special attention was paid to carbon monoxide (CO), which is the most toxic impurity and is contained in an amount of 85...90% in the exhaust gases of road transport. In addition, (CO) is the most conservative gas, whose lifetime in the atmosphere is much longer than that of other exhaust gases.

The concentration (CO) depends on the intensity, speed, composition of traffic flows, and wind speed. However, it is necessary to take into account the toxicity of other types of harmful substances, the effect of which on toxicity is relatively higher than carbon monoxide.

When calculating the concentration of toxic substances in roadside forest space, a method based on the model of turbulent diffusion is recommended, which, after some assumptions, can be reduced to the model of Gaussian distribution in the atmosphere:

$$C = \frac{2q}{\sqrt{2\pi}\sigma_2 U} \cdot \exp \left[ -\frac{1}{2} \left( \frac{H}{\sigma_2} \right)^2 \right],$$

(8)

where $C$ – concentration of toxic substances, g/m³; $q$ – emission, g/s·m; $U$ – wind speed, m/s; $\sigma_2$ – standard deviation of Gaussian scattering in the vertical direction, m; $H$ – height of the roadside point above ground level, m.

The intensity of the release of a toxic substance is determined by the formula:

$$q = \frac{n_1 d_1 + n_2 d_2}{3.6 \cdot 10^5},$$

(9)

where $n_1, n_2$ – the intensity of the traffic flow in the forward and reverse directions, auth./h; $d_1, d_2$ – the average value of the amount of toxic substances released by one of the vehicles of the traffic flow per 100 meters of the path.

The values of $d_1$ and $d_2$ are determined taking into account the composition of the traffic flow

$$d = \sum_{i=1}^{N_i} N_i,$$

(10)

where $N_i$ – the amount of toxic substances released by $i$-the type car per 100 m of the path.

The standard deviation $\sigma_2$ depends on the distance $L$ between the road axis and the desired point of the roadside space, as well as on the weather conditions.

4. Conclusion
The conditions carried out to identify the dependence of the bonus of forest stands on the technogenic impact of road transport on roadside ecological systems is an important factor in theoretical and
experimental studies. The results of the conducted research can be an important tool for monitoring the environmental condition from the technogenic impact of road transport on forest stands located along highways.

The change in the chemical parameters of the soil from the technogenic impact of motor transport at various distances from the highway at a distance of 30-35 m for exchange cations and heavy metals decreases to an insignificant value in the forest plantation and approaches the control at a 100-meter distance. At the same time, it was established that the bonita of forest stands along highways is the most important measure of the quality of the environment, its ecology and can serve as a control parameter for man-made pollution from the emission of motor transport. Analytical dependences are given for predicting the growth rate of forest cover, that is, the bonus depending on the technogenic impact of road transport, and a dependence is also proposed for calculating the intensity of pollutant emissions taking into account the composition of the road traffic flow.

The information obtained because of roadside forest monitoring can be used for the development and implementation of a set of administrative, forestry and other measures to reduce the anthropogenic load on roadside forest ecological systems.

The conducted research is of scientific interest for forest science and forest ecological systems.

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