Mathematical Algorithm for Creating 3D Models of Heat Maps as a Biophysical Method for Assessing Environmental and Economic Fire Damage in the Far Eastern Federal District of Russia

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Abstract

The aim of the research is to create a mathematical and statistical model and its computer implementation in the Python high-level programming language for modeling the dynamics of fire propagation based on satellite images and assessing the environmental and economic fire damage in the far Eastern Federal district of the Russian Federation. Using mathematical and statistical deterministic dynamic Navier-Stokes equations, a method for indicating the state of timberlands in the region has been developed, considering the main characteristics, such as: components of speed in the three-dimensional direction, fire intensity, parameters of fire propagation time and coefficients of fire propagation level depending on the geographical location of fire centers. As a result, a schematic heat map and its three-dimensional prototype in the form of restrictions on economic activity due to natural factors of the regions of the Far North-East and the Far East of Russia were compiled.

Keywords: mathematical algorithm; ecology; biophysics; Far East and North-East; 3D modeling; heat map.

Introduction

The far Eastern region is the largest of the regions of the Russian Federation, with an area of 6,952,555 km², including nine subregions. In 2019, the population of the far Eastern region was 8,188,623, and the population density was 1.18 persons / km².

The overall state of environmental potential in the far Eastern region is characterized by an imbalance in production and natural relations in almost all areas. It causes the violations of the norms for the development and placement of material production and uneven population settlement throughout the territory.

The macroeconomic opportunities of this region of Russia are determined by the main production sectors: mining, the high-tech space industry of the Vostochny cosmodrome and the transfer of

natural resources (the gas pipeline "Sila Sibiri"), as well as the production and distribution of electricity. These economic units form a whole set of sanitary and hygienic problems that have both a direct and indirect impact on the population, including incidence and mortality rate from respiratory, cardiovascular and oncological diseases. The analysis of the environment of the ecological state of the far Eastern region shows that the number of pollutants released into the atmosphere from processing industrial complexes has increased over the period 2014-2017. At the same time, in 2014, emissions from stationary sources amounted to 987.96 thousand tons, and in 2017, the volume of emissions amounted to 1102.12 thousand tons. The main part of the total volume of emissions in 2017 was made up by the Republic of Sakha (Yakutia) and Primorye territory with 50.04 and 64.12 thousand tons, respectively.

Therefore, at present, problems with the health of the population are aggravated due to the unfavorable environmental situation. There is a downward trend in public health across the region. Air, water and soil pollution have been shown to negatively affect health state. Supplies of drinking water and food containing xenobiotics of various origins are environmentally unsafe. Negative environmental factors negatively affect the birth rate and health of newborns. As the population naturally declines, the number of people of working age decreases (Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Kamchatka Territory; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Khabarovsk Territory; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Magadan Region; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in Primorsky Krai; "SCANEX" company; Meira-Castro, 2015; Nunes, 2016).

As a result, it is necessary to develop algorithms and methods for assessing existing natural resources, types and territories of their location. This is an important component for developing an ecological and economically balanced strategy for sustainable natural resource management in the Northern and Eastern territories of Russia and their future development.

Currently, the entire population of the far Eastern region is under threat of forest fires, the main representatives of which are Russians, Ukrainians, Yakuts, Koreans and small groups of core nations (Evens, Nanais, Koryaks, etc.). The far Eastern region is characterized by diversified industrial production, which leads to the presence of a large number of sources of environmental pollution with fire-hazardous substances that cause serious environmental and economic problems in the territory (Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Kamchatka Territory; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Khabarovsk Territory; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Magadan Region; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in Primorsky Krai; Meira-Castro, 2015).

International scientific results of research in this area show a close relationship between the state of the environment and diseases of various etiologies (Abberton, 2016; Hannis, 2015; Giglio, 2016).

Negative environmental factors negatively affect the birth rate and health of newborns. As the population naturally declines, the number of people of working age decreases (Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Kamchatka Territory; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Khabarovsk Territory; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Magadan Region; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in Primorsky Krai; "SCANEX" company; Meira-Castro, 2015; Nunes, 2016).

The purpose of this study is to assess the ecological and economic situation in the far Eastern region and draw up a schematic heat map and its three-dimensional prototype as a method of observing the dynamics of fire propagation and predicting them in the future.

To achieve this goal, the following tasks were completed:

1. Assessment of the medical and demographic situation in the far Eastern region;
2. Consideration of the map of forest fires in the far Eastern Federal district;
3. Building a heat map of fire propagation;
4. Development of a 3D modeling algorithm and its implementation in the Python.

Methods

The traditional method for modeling the behavior of a forest fire is to represent all the points of ignition at the fire site in the ellipse form. Sometimes this method is not informative, since the modeled result is very different from the real situation and is mainly applicable to relative fire centers on a large, almost flat surface (Figure 1). As a result, the rendered information is limited. This study uses a fire propagation model based on the Navier-Stokes equations and dynamical systems theory to model the behavior of a forest fire in various wind positions and directions. The results are shown by a system based on the concentration gradient of peaks in 3D depending on the intensity, which not only allows you to get the area of fire damage, the direction of fire propagation and the size of the fire, but also provides a realistic simulation for observers. The method was successfully applied to the forest of the far Eastern Federal district in the subjects of the Russian Federation: Primorye, Khabarovsk, Kamchatka territory, Magadan region and the Republic of Sakha (Yakutia) (Barlow, 2016; Ekaputri, 2016; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Kamchatka Territory; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Khabarovsk Territory; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Magadan Region; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in Primorsky Krai; Meira-Castro, 2015).

**Figure 1. Satellite image of SCANEX Russia d.d. August 15, 2019
during forest fires in the far Eastern Federal district**

Dynamical systems theory is a field of mathematics that is used to describe the behavior of complex dynamical systems. In the theory of dynamical systems, differential equations or difference equations are usually used (Hannis, 2015; Giglio, 2016; Nunes, 2016; Singh, 2016; Li, 2017; Bright, 2017). The theory of dynamical systems is called a continuous dynamical system if the system uses a differential equation. Continuous dynamical systems, from the physical point of view, are generalized using classical mechanics. The implementation of continuous dynamical systems is usually postulated directly, which is not limited to the Euler-Lagrange equation (Abberton, 2016; Hannis, 2015; Giglio, 2016; Nunes, 2016; Li, 2017). The theory of dynamical systems is called a discrete dynamical system if the system uses a finite-difference equation. When a time variable runs through a discrete set for several intervals and continues for another interval, it will get dynamic equations on a time scale. Some situations can also be modeled by mixed operators, such as differential-difference equations (Barlow, 2016; Ekaputri, 2016; Hannis, 2015; Meira-Castro, 2015; Singh, 2016; Nebylova, 2014).

A dynamical system at any moment has a state represented by a set of real numbers that can be illustrated by a point in the corresponding space (Giglio, 2016; Iu, 2018; Khvan, 2015). Changes in the rules of the dynamic system are functions that present forecasts of future circumstances based on real data of the current situation (Hannis, 2015; Giglio, 2016; Bright, 2015; Stepanko, 2015; Iu, 2018). The function of a dynamic system is often deterministic, and only one future state follows from the current state data at certain time intervals (Singh, 2016; Bright, 2017; Nebylova, 2014). However, some systems are stochastic, and functions in these random events also affect the evolution of state variables (Li, 2017; Bright, 2015; Stepanko, 2015; Iu, 2018). To predict the future behavior of the system, an analytical solution of such equations or their integration in time using computer modeling is implemented (Nebylova, 2014; Stepanko, 2015; Khvan, 2015).

In this model, the fire is represented as a model of water distribution, as a system in which it is difficult to model the corresponding flow (Ekaputri, 2016; Giglio, 2016; Nunes, 2016; Bright, 2015). The three-dimensional behavior in an environment in which at any point the wave speed will change a function of location (x, y), fire intensity (z) and time (t) is the reason, that forest fire phenomena is difficult to understand and predict in detail (Giglio, 2016; Singh, 2016; Nebylova, 2014). In these cases, only three-dimensional models are feasible for the correct description of fire propagation events in woodlands (Nunes, 2016; Singh, 2016; Bright, 2015).

Then the main assumptions taken in the derivation of equations, as well as boundary and initial conditions:

1. The forest is a multiphase, multi-storey, spatially heterogeneous environment;
2. In the fire zone, the forest is a porous-dispersed two-temperature reaction medium with a single speed;
3. The forest canopy is assumed to be an undeformed medium (trunks, large branches, small twigs, and needles), which only affects the resistance force in the equation of momentum conservation in the gas phase, i.e. the medium is considered as quasi-solid, i.e. practically inflexible during wind flows;
4. Let there be a so-called "ventilated" forest area in which the volume of fractions of condensed forest fuel phases consisting of dry organic matter, water in a liquid state, solid pyrolysis products and ash can be neglected in comparison with the volume fraction of the gas phase (components of air and gaseous pyrolysis products);
5. The flow has a developed turbulent nature, and the transfer of molecules is neglected;
6. The density of the gas phase is independent of the pressure due to the low flow rates compared to the speed of sound;

7. The spread of fire is uncontrolled in all planes and in any direction;

8. The transition to other levels occurs spontaneously and without the possibility of reducing the speed of this process.

Let the coordinate reference point $x, y, z = 0$ be located in the center of the surface source of a forest fire at a height of 1 meter from the ground. The $0x$ axis is directed parallel to the ground to the right of undisturbed wind speed direction. The $0y$ axis is directed perpendicular to $0x$, and the $0z$ axis is directed upward (Hannis, 2015; Giglio, 2016; Iu, 2018).

Also, the system of equations (3) describing 3D models must be solved taking into account the initial and boundary conditions based on the Navier-Stokes equations, i.e.:

$$\begin{cases} p * \frac{du}{dt} = -\frac{\partial p}{\partial x} + \frac{dr_{xx}}{dx} + \frac{dr_{yx}}{dy} + \frac{dr_{zx}}{dz} + p * f_x \\ p * \frac{dv}{dt} = -\frac{\partial p}{\partial x} + \frac{dr_{xx}}{dx} + \frac{dr_{yx}}{dy} + \frac{dr_{zx}}{dz} + p * f_y \\ p * \frac{dq}{dt} = -\frac{\partial p}{\partial x} + \frac{dr_{xx}}{dx} + \frac{dr_{yx}}{dy} + \frac{dr_{zx}}{dz} + p * f_z \end{cases} \quad (3)$$

where u, v и q - components of speed in the direction x, y и z , p - the intensity of the fire. The parameters t are the fire propagation time, and f is the rate of fire spread.

These equations are discrete dynamical systems (Hannis, 2015; Bright, 2015; Iu, 2018). When a variable time passes through a discrete set of intervals and continues for another interval, it generates a dynamic equation on the time scale (Singh, 2016; Nebylova, 2014; Iu, 2018). Some situations can also be modeled by additional operators, such as differential operators.

As you know, these equations are quite difficult to integrate, but for simple cases, usually associated with two-dimensional phenomena, they can be successfully used.

Results

As an example, a three-dimensional model based on satellite photos of the SCANEX Engineering and technology center ("SCANEX" company) d.d. August 15, 2019 during forest fires in the far Eastern Federal district was created using a mathematical algorithm formalized by the Python programming language to identify potential fire sources and assess the corresponding hazards and compare their effectiveness and stability against two-dimensional methods (Figure 2).

The boundary value problem in modeling chaotic models is solved numerically. The range of temperature, propagation, speed and, respectively, the concentration of the gas phase and the volume fractions of condensed phases were obtained numerically. The distribution of the main functions shows that the process of initiating a forest fire goes through the following stages. The first stage is associated with the beginning of a forest fire. At this stage of the process, a thermal wind is formed over the source of the fire - a zone of heated forest fires of pyrolysis products that mix with the air, float up and penetrate the crowns of trees. As a result, tree trunks are heated, moisture is vaporized and gassed, and toxic products of dispersed pyrolysis are formed. At the next stage, the gaseous pyrolysis products of the soil cover are ignited and the concentration of gaseous pyrolysis products in the forest canopy increases at the last stage. Due to the additional heating, the moisture evaporates, and pyrolysis occurs accompanied by the release of secondary gaseous products, which then ignite and burn in the forest canopy. At the moment of gas ignition, the combustible pyrolysis products burn with a rapid decrease in the oxygen concentration.

The temperatures of both phases reach the maximum value at the point of ignition.

Therefore, in this 3D model, the z -axis represents the intensity of fire propagation (in%), the s -plane is formed by x and y axes (respectively, the length and width of the image). In Figure 2, the numbers are: 1-Magadan; 2-Petropavlovsk – Kamchatsky; 3 – Vladivostok; 4-Khabarovsk.

Methods of algorithmic analysis of the forest fire level, building models of heat maps and their 3D images of processes, and factor analysis allowed analyzing the main fireplaces based on a set of observation data in order to assess the level of environmental disaster and economic damage to the territory of the far Eastern Federal district. Statistical models are based on the assumption that the modeled process is random and is investigated using statistical methods. The criteria for assessing the level of environmental and economic damage in the region were such indicators as the intensity of fire, the components of fire propagation. Such components can be used as control variables that characterize the economic state of the region and additional factors that affect the health of the population: the availability of water sources, population density, as well as the share of the working population.

Figure 2. A 3D-model of a heat map of fire propagation in the far Eastern Federal district

Discussion

Three dimensional models are much more difficult to describe than conventional two-dimensional images and the calculation time for them is longer due to the stochastic and multicomponent three-dimensional behavior of the environment (Ekaputri, 2016; Giglio, 2016; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in the Magadan Region; Office of the Federal Service for Supervision of Consumer Rights Protection and Human Welfare in Primorsky Krai). In addition, a set of detailed data is required to simulate a fire event. In fact, a wave of fire flow moves across the plain for several days or weeks, and even if a high-precision instrument makes observations (fire intensity, fire propagation zone), it is only in certain places and times.

Conclusion

In general, the use of 3D models should be limited to special cases, such as:

- when the results obtained using two-dimensional fire propagation equations are not reliable enough due to the fact that the time of fire propagation and the intensity of fire cannot be ignored;
- when a 3D flow model is relevant to the spread of pollutants, fire risk assessment, and development of emergency and evacuation plans.

Forest fires are among the most destructive natural disasters and may become more frequent, destructive and relevant in the future due to the effects of population growth, urbanization, land reclamation and, to some extent, climate change.

A forest fire is an uncontrolled chaotic event of great complexity. The thermal parameters of a fire (size, intensity of fire, speed, prevalence on the territory and duration) reflect the stochastic behavior of infiltration, total evaporation, dryness of the soil, land, changes in the conditions of the forest ecosystem.

The quality of the environment is one of the most discussed issues affecting absolutely all spheres of human activity. Thus, the concept of ecology is inextricably linked with health. Therefore, these studies look at the impact of environmental quality on morbidity and life expectancy in one way or another.

Traditional measures taken to improve public health include: sanitary control over the cleanliness of the environment; prohibition of smoking in public places; provision of preventive medical services; body conditioning, etc. Due to the complexity of regulating industrial activity in the far Eastern region and taking into account the risk factors, the rate of the non-specific resistance of the human body is possible only through nutrition by creating functional products containing local adaptogens. This might be, for example, lemongrass, *Eleutherococcus*, shizandra, which optimize the homeostasis of the substance and contain a unique complex of biologically active substances.

The results of the simulation make it possible to assess the critical state of forest fire propagation, which allows us to use this model to prevent fires and assess economic damage from them. It estimates the fire propagation by taking into account the intensity of fire in forests, which depends on the properties of the crown: poured density, moisture content in the tree trunk, and so on. The proposed model provides a detailed picture of changes in the fields of fire speed, temperature and concentration of components over time, and also determines the influence of various conditions on the beginning of a forest fire using satellite images. The results obtained are consistent with the laws of physics and statistical parameters of dynamical systems.

Dynamical systems theory can be applied to various fields of science, such as mathematics, physics, biology, chemistry, engineering, economics, and medicine. Dynamical systems are a fundamental part of chaos theory, logistics map dynamics, bifurcation theory, the self-assembly process, and the concept of the edge of chaos. This article provides an example of applying the theory of dynamic systems with the approach of creating 3D models of heat maps of forest fires in real time. In this study, the presented prototypes not only help in understanding the phenomena of forest fires, but are also important for assessing the risk of their occurrence and spread in the current situation and for assessing the expected changes.

Mathematical algorithms with information implementation in the form of 3D models are useful tools for developing effective flood protection strategies and conducting a comprehensive cost-benefit analysis of a specific measuring proposals to level the impact of natural disasters.

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