Influence of the canopy structure of a birch forest on the visibility of the fires below

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Abstract. The work is aimed at studying the visibility of a flame through the canopy of a birch forest, depending on the structure of the latter, and providing support for decision-making on the choice of the optimal sensing geometry for solving the problem of detecting fires in birch forests when video shooting from low altitudes. For the site located in the Priozersk district of the Leningrad region, using photographic technology, data were obtained on the frequency distribution of birch leaf inclination angles (for a hybrid of two species). The information is compared with the results of the work of other researchers. On the basis of the collected data, three-dimensional models of the canopy of various structures were constructed, suitable for simulating the radiation transfer. A set of experiments has been carried out to estimate the values of the fraction of beam penetration for light emitted by the combustion center in the direction of the sensor at different viewing angles. For individual ratios of crown sizes and distances between them, the least informative ranges of viewing angles, which should be avoided when monitoring fires, have been determined. It has been confirmed that the visibility of the flame depends on the shape and closeness of the crowns, which determine the length of the radiation path in the vegetation layer, and, to a lesser extent, on the prevailing orientation of the leaves.

1. Introduction
Unmanned aerial vehicles equipped with visible and infrared cameras are increasingly used to detect fires within forest areas [1]. However, most of the methods for automatic detection of combustion foci from aircraft and satellite platforms are focused on detecting a developed fire as an area object [2, 3]. Finding solutions that allow for earlier detection of hazards is a key success factor in preventing and responding to these types of emergencies. The problem of detecting fires at the initial stage is especially urgent for monitoring compliance with the appropriate fire-prevention regime in suburban forests, in nature reserves. To monitor small-sized combustion foci, sensing from low altitudes is used [4]. In this case, the prompt survey of vast territories requires the use of a large number of unmanned aerial vehicles. Despite the shortcomings of imaging systems in the visible range, their use for solving such a problem looks more preferable than the option of using IR cameras, largely for economic reasons.

The influence of the structure of the forest canopy on the possibility of detecting small-sized flames from the air is currently poorly studied. Appropriate experiments are required to select the sensing geometry and shooting modes that could provide the required fire control efficiency.
The purpose of this work is to provide information support for decision-making on the choice of sensing geometry and shooting modes for controlling fires in birch forests.

In the course of the study, the problem of collecting and analyzing data on the peculiarities of the spatial arrangement of foliage elements in the canopy of a birch forest is solved; on the basis of the collected data, virtual models of the canopy are created, suitable for numerical simulation of radiation transfer. Also, within the framework of the work, a series of experiments are being carried out to estimate radiation transmittance by a canopy and to analyze the visibility of a flame located under a canopy with given characteristics.

2. Materials and methods
The work is divided into three main stages, at each of which a specific research problem is solved and a certain set of materials, methods and tools is used.

2.1. Collecting data on the features of the spatial arrangement of phytoelements
At this stage, open sources for information on the orientation of leaves of different birch tree species. Also, at the test site located in the Priozersky district of the Leningrad region (coordinates of the center of the site 60.5600 °N, 30.3307 °E), a set of field works was carried out to clarify the leaf angle distribution in birch crowns. The values of leaf inclination angles were obtained using the method proposed in [5] and is currently actively used to collect data in various climatic zones. Alternative approaches [6-8] are much more complicated in technical implementation and are applicable in a limited range of conditions. In the course of field work, fragments of crowns were shot at different heights with a leveled Nikon D3200 camera with a zoom lens from a distance of at least 5 m.

Increasing the focal length while maintaining the specified distance and further selecting leaves that are closest to the horizontal straight line dividing the frame in half made it possible to avoid significant errors related to perspective distortion. A truck-mounted aerial platform was used to ascend to a specific height, a tripod with a bubble level was used to control the horizontal position of the optical axis, and a Bosch GLM 80 laser rangefinder was used to measure distances. Thus, fragments of crowns of 4 birches were surveyed, identified as a mixture (hybrid) of Betula pendula and Betula pubescens. Using the Fiji distribution of the ImageJ software toolkit [9] from the images taken the values of the tilt angles of leaves perpendicular to the frame plane were determined, and the obtained values were combined into a single base indicating the heights at which the corresponding frames were taken.

2.2. Creation of virtual models of canopy fragments
At this stage, the collected information on the frequency distribution of leaf inclination angles was analytically described using two-parameter Beta functions (according to [10,11]), and the obtained functional dependencies were used to generate three-dimensional 3D model representations. For the analytical description of the structure of the canopy, construction and saving of virtual spatial models to external files, the software environment and programming language R [12] was used in combination with a set of additional libraries. In particular, the description of the structure and visualization of the models was carried out using the functions of the rgl package [13]. Also, at this stage, a program code has been prepared to describe the propagation of radiation through the canopy based on the Lambert-Beer model approach (the application of the model is shown, for example, in [14]).

To implement the required set of model experiments to analyze the visibility of the flame, models of three main types were built:

- Type 1. Model in the form of a hemispherical shell of constant thickness, filled with foliage elements. It is necessary to assess the influence of the orientation of foliage elements on the visibility of a flame located under the crown of a freestanding tree, whose branches and leaves block the radiation path in a wide range of vertical angles.
• Type 2. Model in the form of a parallelepiped block extended in two horizontal directions, filled with foliage elements. It is necessary to assess the visibility of the flame through the most closed canopy.

• Type 3. Model in the form of an array of spherical crowns located at a certain distance from each other. It is necessary to simulate a canopy with different values of crown density.

The linear virtual dimensions of the models and their complexity were selected based on the need to provide the possibility of modeling on office-class "laptop" computers (with an Intel Core i5 processor, 8 GB of RAM, 2 GB of video memory). As a result, all constructed models consist of 300 thousand - 850 thousand polygons, and the canopy height is 4 m. The filling with foliage elements during the generation of canopy models was carried out in accordance with the data on the leaf area index (LAI) and the size of leaves. The leaf shape was approximated by a convex polygon. The leaf area index values were chosen over a wide range based on work [15], where young trees of small height are considered. The models were saved in StereoLithography (.stl extension) and 3D Studio Scene (.3ds extension) files.

2.3. Virtual experiments to estimate the transmittance of radiation by canopy and analyze the visibility of the flame

At the stage of virtual experiments, the main tools were the R programming language and specialized software for lighting design from DIAL GmbH. Three-dimensional scenes were previously prepared, each of which, in addition to the canopy model, included models of reflecting surfaces, a model of a radiation source (combustion center), a system of models of point radiation sensors, a system of test sensitive surfaces, and a model of daylight.

The reflectivity of the object models was established according to the information available in open sources. The sensors and sensitive surfaces were positioned in virtual space in such a way as to provide a quantitative assessment of the source light, propagating in different directions and penetrating the canopy. In each scene, the source radiation energy was detected at elevation angles of 15-85 degrees from the horizontal plane (this range is selected taking into account the sizes and geometric proportions of the models used). As the main informative parameter, estimated in the course of experiments, the fraction of beam penetration (the transmission coefficient) in given directions was chosen. The experiments involved 10 scenes with models of type 1 and 4 scenes each with models of types 2 and 3.

Also, at this stage, calculations of the transmission coefficient were performed using the Lambert-Beer model (one-dimensional model of the "cloud layer") based on the same initial data on the leaf angle distribution. The coefficient estimates were obtained by determining the values of the Ross-Nilson integral function (G-function), which expresses the fraction of the projected area created by a unit of foliage area on the plane perpendicular to the direction of radiation propagation (depending on the angle defining the tilt of the viewing beam from the nadir/zenith) [16].

3. Results and discussion

The search for information on the leaf angle distribution for different species of birches showed that in most studies, the orientation of leaves of silver birch (Betula pendula), dwarf birch (Betula nana), and paper birch (Betula papyrifera) is estimated. Downy birch (Betula pubescens), which, along with silver birch, is one of the most widespread tree species in the territory of the Russian Federation, in the works devoted to the analysis of the canopy structure, no sufficient attention is paid.

The type of distribution for silver birch varies from study to study and depends both on the characteristics of the surveyed canopy and on the instruments used [8, 17-19]. Figure 1 (a) shows a histogram of the values of the leaf inclination angles θ, built according to the data of [20] (where the method we have chosen [5] is also used). Leaf angle distribution obtained in this study as a result of field and office work for the hybrid Betula pendula and Betula pubescens in the test site is shown in figure 1 (b). The presented distributions have significant similarities with each other and have features of both planophilic and plagiophilic distributions.
We also obtained the parameters of Beta functions approximating the distributions, which are necessary for further modeling. The data [20] are best described by a function with $\mu = 2.02$, $\nu = 1.13$, the data obtained in the framework of this study, by a function with $\mu = 2.67$, $\nu = 1.27$.

Figure 1. Leaf angle distribution according to research data [20] (a) and data obtained as a result of field work at the test site (b); green line - approximation by two-parameter Beta function.

The inclination angle of each individual leaf when creating three-dimensional models of the canopy was extracted from a sample generated based on the distribution function with the specified parameters. Examples of the obtained spatial models of the three types described earlier are shown in figure 2.

The angular variability of the fraction of beam penetration through the canopy $\gamma$ for models of types 1 and 2, retrieved in the course of virtual experiments and expressed graphically, is shown in figure 3. As can be seen from the image, barriers in the form of groups of leaves cause the appearance of local minima of illuminance on sensitive surfaces equidistant from the light source (minima of $\gamma$ in a given direction), which, as a result, gives a rather motley picture of the variability of $\gamma$. This pattern of variability is observed when considering variations in $\gamma$ in 5-10-degree angular intervals (both horizontal and vertical angles). When comparing the values for different intervals of the viewing/elevation angle $h$ (the angular height of the sensor above the horizon), a variability of another scale is revealed - the dependence of $\gamma$ on the viewing angle $h$. The type of this dependence is determined by the type of canopy model used in the scene. So, for models in the form of a hemispherical shell, with increasing $h$ (figure 3 (a)), a decrease in the average values of $\gamma$ in 10-degree intervals is noted, associated with a significant proportion of leaves with small and medium angles of inclination. Those, at large $h$, the light of the source, overcoming the same distance, encounters more barriers in the form of foliage elements. In experiments with scenes containing type 2 models (figure 3 (b)), at small $h$, light travels a much longer linear path through the canopy, and this affects the change in transmittance to a greater extent than the prevailing orientation of the leaves.

Figure 2. Examples of canopy models used in virtual experiments: (a) Model in the form of a block-parallelepiped; (b) Hemispherical shell model; (c) Model in the form of an array of spherical crowns.
Figure 3. Examples of angular dependences $\gamma$ according to the results of experiments using two types of models: (a) Model in the form of a hemispherical shell, LAI = 3.6; (b) Model in the form of a block-parallelepiped, LAI = 1.7.

Figures 4, 5 show the graphs of the dependence $\gamma = f(h)$ for models of types 1 and 2 according to the data of virtual experiments (black curves) and according to the data of calculations using the Lambert-Beer model (blue curves). The dots represent average $\gamma$ values for 10-degree viewing angle intervals (for 3D scenes - and azimuth angle). In the case of simulating the propagation of radiation through three-dimensional canopy models, the resulting $\gamma$ values shown in the graph for each angular interval are obtained by averaging over all scenes containing models of this particular type.

The presented graphs show the features of the angular variability already described above. The discrepancies between the simulation results based on 3D models and the Lambert-Beer model are within the 95% confidence interval of the mean for models 1 and 2. The difference in the position of the corresponding curves is most likely associated with the scale of inhomogeneities (leaf sizes), which give a scattering effect that is not taken into account in the Lambert-Beer model.

Figure 4. Dependence of the transmission coefficient $\gamma$ on the viewing angle $h$ (from the horizontal) for a model of type 1 (hemispherical shell) at LAI = 3.6

Figure 5. Dependence of the transmission coefficient $\gamma$ on the viewing angle $h$ (from the horizontal) for a model of type 2 (block-parallelepiped) with LAI = 1.7
Modeling with Type 3 Models (array of spherical crowns) provides insight into flame visibility in more common low-altitude fire control situations. In the case under consideration, the crowns in the canopy are not completely closed, and their shape is close to a sphere. In the course of experiments with models of this type, the dependences $\gamma = f(h)$ were obtained for different positions of the radiation source (combustion center) relative to the crown. Figure 6 in the polar coordinate system shows an example of such a dependence for the center of a source, shifted by 1.5 m from the center of the crown projection onto the earth's surface, with a crown diameter of 3 m and a distance between their centers of 4.25 m.

The image also shows the location of the crowns and the source, the ray traces that set the direction of view are highlighted. Figure 7 shows the change in the form of the angular dependence when the center of the source is displaced relative to the projections of the crowns (in the case under consideration, the displacement $m$ changes with a step of 0.5 m from -0.5 m to 1.5 m). As can be seen from the image, even at a given ratio of the distance between the crowns to their diameter (and height) at small viewing angles (up to $40^\circ$), it is possible to detect a flame, regardless of its position relative to the crowns, only with a small leaf index. With an increase in crown density, the sensing geometry approaches that considered for type 2 models (and the flame visibility will be limited primarily by LAI). So, the contact of crowns of the same size leads to the fact that the range of fluctuations $\gamma$ is significantly smaller, and flame detection at high leaf area index values is difficult even at angles up to $65^\circ$. In the case of a sparser canopy, it becomes possible to use small viewing angles (this makes it possible to detect flames near the barrels).

When shooting with a camera in motion, viewed light rays within angular field of view will intersect more and less sparse sections of the canopy. As a consequence, the ability to detect a flame under a canopy will depend on the focal length of the lens of the video camera system used. Experiments with the considered sensing geometry suggest that the use of wide-angle lenses may be preferable for solving such a problem.

![Figure 6. Angular dependence $\gamma = f(h)$ according to the results of experiments using a model of type 3, LAI = 0.65. The crowns, the centers of which are located in the same plane with the directions of viewing, are indicated in green, and the combustion center is in orange.](image-url)
Figure 7. Angular dependence $\gamma = f (h)$ according to the results of experiments using the model of type 3, LAI = 0.65, at different values of the displacement $m$ of the light source relative to the crowns.

The demonstrated experimental results show that the structure of the canopy has a significant effect on the ability to detect a flame under the canopy from the air in the visible range. However, the detection efficiency will depend not only on the choice of the sensing geometry, but also on the lighting conditions during shooting. In many cases, the brightness of the light source on a sunny day will not be enough to create the necessary contrast on the image detectors of the camera, and in this case, it will be possible to detect a fire only by the color and certain types of flame pulsations. Conversely, in low ambient light conditions, even with substantial canopy shading, a flame is more likely to be detected, especially when using appropriate sighting schemes.

4. Conclusion
During the study, new data were obtained that can be used to make decisions on the choice of shooting modes and sensing geometry when monitoring fires in birch forests.

The created model descriptions are suitable for studying the possibility of detecting objects of different types when shooting from the air, as well as for modeling in the field of electrodynamics and radio wave propagation, biometeorology and agroecology.

The written program code is planned to be used to generate more detailed canopy models. Experiments on the estimation of the radiation transmittance and the analysis of the flame visibility under the canopy will be continued with the introduction into the scenes of models with a different crown shape and a different inter-crown distance, as well as models of trees of other species. The study is also planned to be supplemented with field experiments on analyzing the visibility of the flame in the conditions of real forests.

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