MATHEMATICAL MODELING OF THE IMPACT OF FIREBREAKS AND BARRIERS ON THE SPREAD OF CROWN WILDFIRES

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Abstract: The paper presents a numerical study of the effectiveness of firebreaks and barriers on the wildfires spread using mathematical modeling. The paper considers firebreaks, fire barriers made of deciduous trees, and its combination. During the calculations, the wind velocity, reserve, and moisture content of coniferous and deciduous wood have been changed. The results have shown that fire barriers made of deciduous trees are more effective under conditions of high moisture content of deciduous wood and low wind velocity. The effectiveness of fire barriers and firebreaks depends on its size and combination. Optimal sizes of firebreaks and fire barriers were determined based on numerical modeling. To effectively prevent the spread of wildfire, it is recommended to use firebreaks as well as its combination with fire barriers. Thus, with the combined use of firebreaks and fire barriers, the area of unused land is reduced by 30%.

Keywords: wildfire; crown fire; firebreak; fire barrier; mathematical modeling; numerical solution; control volume method

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Figure Captions

Figure 1 Scheme of the solution domain: *1* — ignition source; *2* — coniferous forest area; *3*— firebreak; *4*— fire barrier; x_1, x_2 and y_1, y_2 — coordinates of the beginning and the end of fire barrier along OX and OY, respectively; and X and Y — sizes of the barrier along the corresponding axes

Figure 2 Dependence of the size of a fire barrier area made of deciduous trees on its moisture content, $y = 48.554x^2 - 558.38x + 1480.9$

Figure 3 Dependence of fire barrier area on wind velocity, $y = 1237.1x^{-0.41}$, $R = 0.995$

Figure 4 Distribution of isotherms in the fire front before and after the firebreak at wind velocity of 4 (*a*) and 8 m/s (*b*) at times t: I — 5 s, II — 6; III — 13; and IV — 16 s. Distribution of gas phase isotherms: *1* — $\overline{T} = 5$; *2* — 3; *3* — 2; and *4* — $\overline{T} = 1.3$

Figure 5 Comparison of firebreaks and fire barriers sizes: (*a*) stock of forest combustible material 0.5 kg/m^3, moisture content of coniferous forest 0.66, wind velocity 7 m/s, and moisture content of barrier 1.0; (*b*) stock of forest combustible material 0.66 kg/m^3, moisture content of coniferous forest 0.2, wind velocity 7 m/s, and moisture content of barrier 1.0; and (*c*) stock of forest combustible material 0.2 kg/m^3, moisture content of coniferous forest 0.2, wind velocity 7 m/s, and moisture content of barrier 1.0

Table Captions

Table 1 Fire barrier dimensional characteristics depending on the moisture content of the deciduous forest combustible materials

Table 2 Area characteristics of the fire barrier depending on the moisture content of the deciduous forest combustible materials

Table 3 Dimensional characteristics of deciduous tree firebreaks depending on wind speed

Table 4 Area characteristics of deciduous tree firebreaks depending on wind speed

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References

1. Lee, B. S., M. E. Alexander, and B. C. Hawkes. 2006. Assessing the effectiveness of operational fuel treatments against wildfires in Canada. *Can. J. Forest Res.* 36(11):2961–2970.
2. Ascoli, D., L. Russo, F. Giannino, C. Siettos, and F. Moreira. 2018. Firebreak and fuelbreak. *Encyclopedia of wild-*

fire and wildland–urban interface (WUI) fires. Cham: Springer. 444–452.

3. Finney, M.A. 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *Forest Sci.* 47(2):219–228.
4. Catchpole, W. R., R. A. Bradstock, J. Choate, L. G. Fogarty, N. J. H. Gellie, G. J. McCarthy, and L. J. Wright. 1998. Cooperative development of equations for heathland fire behavior. *3rd Conference (International) on Forest Fire Research Proceedings*. 631–645.
5. Sturtevant, B. R., D. T. Cleland, T. R. Crow, and S. M. Lietz. 2004. The role of wildfire in the Great Lakes mixed deciduous-conifer forest: Modeling restoration strategies in a multi-owner landscape. *Restor. Ecol.* 12(1):52–63.
6. Alexander, M. E., and M. G. Cruz. 2013. Are the applications of crown fire behavior modeling systems getting ahead of their evaluation again? *Environ. Modell. Softw.* 41:65–71.
7. Kobziar, L. N., D. R. Godwin, L. Taylor, and A. C. Watts. 2015. Perspectives on trends, effectiveness, and impediments to prescribed burning in the southern US. *Forests* 6(3):561–580.
8. Pimont, F., J. L. Dupuy, R. R. Linn, and S. Dupont. 2019. Impact of fuel moisture content and wind speed on fire behavior in a shrubland ecosystem: A physics-based modeling approach. *Int. J. Wildland Fire* 28(6):494–510.
9. Chuvieco, E., I. Aguado, and M. Yebra. 2014. Development of a framework for fire risk assessment using remote sensing and geographic information system technologies. *Ecol. Model.* 221(1):46–58.
10. Khan, N., and K. Moinuddin. 2021. The role of heat flux in an idealised firebreak built in surface and crown fires. *Atmosphere — Basel* 12:1395.
11. Brou, A. D. V., T. D. Soro, and K. K. S. Yanga. 2025. Critical threshold for crossing a firebreak: Mathematical model and fire experiments. *CR Mécanique* 353:673–686.
12. Yemshanov, D., N. Liu, E. W. Neilson, F. H. Koch, and M.-A. Parisien. 2025. Evaluating fuelbreak strategies for compartmentalizing a fire-prone forest landscape in Alberta, Canada. *PLoS ONE* 20(5):e0321722.
13. Van Aardt, A. C., J. C. L. de Jager, and J. J. van Tol. 2024. Firebreaks and their effect on vegetation composition and diversity in Grasslands of Golden Gate Highlands National Park, South Africa. *Diversity* 16:373.
14. Hoffman, C. M., J. M. Canfield, R. R. Linn, C. H. Sieg, and D. A. Falk. 2018. Simulating fire behavior and restoration treatments using a coupled fire–atmosphere model. *Fire Ecol.* 14(1):1–19.
15. Perminov, V. A. 2023. Numerical solution of the crown forest fires spread taking into account fire barriers and breaks. *Recent developments in the field of non-destructive testing, safety and materials science*. Eds. E. Lysenko, A. Rogachev, and O. Stary. Studies in systems, decision and control ser. Springer. 433:155–164.
16. Gannon, B. M., Y. Wei, E. J. Belval, *et al.* 2023. A quantitative analysis of fuel break effectiveness drivers in Southern California national forests. *Fire* 6(3):104.
17. Ortega, M., F. Rodriguez y Silva, and J. R. Molina. 2024. Modeling fuel break effectiveness in southern Spain wildfires. *Fire Ecol.* 20:40.
18. Hayajneh, S. M., and J. Naser. 2025. Wind and slope influence on wildland fire spread: A numerical study. *Fire* 8(6):217.
19. Park, J., M. Moon, T. Green, *et al.* 2024. Impact of tree species composition on fire resistance in temperate forest stands. *Forest Ecol. Manag.* 572:122279.
20. Harris, M. P., J. D. Coop, J. A. Balik, *et al.* 2025. Aspen impedes wildfire spread in southwestern United States landscapes. *Ecol. Appl.* 35(5):e70061.
21. Kwon, K., S. Kim, S. Lee, *et al.* 2021. Analysis of crown fire transition and spread over various pine trees using wildland–urban interface fire dynamic simulator. *J. Korean Social Hazard Mitigation* 21(4):31–38.
22. Zhuang, H., N. Liu, X. Xie, *et al.* 2025. Simulating wildfire spread based on continuous time series remote sensing images and cellular automata. *Int. J. Wildland Fire* 34(1):1–14.
23. Atchley, A. L., C. M. Hoffman, S. R. Bonner, *et al.* 2024. Evaluating crown scorch predictions from a computational fluid dynamics wildland fire simulator. *Fire Ecol.* 20:71.
24. Grishin, A. M., A. D. Gruzin, and V. G. Zverev. 1985. *Matematicheskaya teoriya verhovykh lesnykh pozharov* [Mathematical theory of crown wildfires]. Novosibirsk: Publishing House of the Institute of Forest Physics SB RAS. 38–75.
25. Grishin, A. M. 1992. *Matematicheskoe modelirovanie lesnykh pozharov i novye sposoby bor'by s nimi* [Mathematical modeling of wildfires and new methods of fight them]. Novosibirsk: Nauka. 404 p.
26. Perminov, V. 2011. *Matematicheskoe modelirovanie lesnykh pozharov. Vozniknovenie verkhovyh i massovykh lesnykh pozharov* [Mathematical modeling of wildfires. The occurrence of crown and mass wildfires]. Saarbrücken, Germany: LAP LAMBERT Academic Publishing. 288 p.
27. Patankar, S. V. 1980. *Numerical heat transfer and fluid flow*. New York, NY: Hemisphere Publishing Corp. 197 p.
28. Guo, H., Z.'Wang, Y. Wang, *et al.* 2023. Experimental analysis on the behaviors of a laboratory surface fire spreading across a firebreak. *Forests* 14(6):1176.
29. Morvan, D. 2015. Numerical study of the behaviour of a surface fire propagating through a firebreak built in a Mediterranean shrub layer. *Fire Safety J.* 71:34–48.
30. Awad, C., A. Lamorlette, and Z. Younsi. 2020. Effects of fuel moisture content and wind speed on fire spread using a multiphase formulation. *Int. J. Wildland Fire* 29(9):774–788.
31. Wilson, A. A. G. 1988. Width of firebreak that is necessary to stop grass fires: Some field experiments. *Int. J. Wildland Fire* 1(1):35–50.
32. Baijnath-Rodino, J. A., B. M. Collins, C. L. Tubbesing, *et al.* 2023. Quantifying the effectiveness of shaded fuel breaks in the Sierra Nevada, California, USA. *Forest Ecol. Manag.* 532:120748.

33. SNiP 2.05.13–90. 1990. *Nefteproduktoprovody, prokladyvaemye na territorii gorodov i drugikh naselennykh punktov* [Oil product pipelines laid in the territory of cities and other populated areas]. Moscow: Gosstroy Publs. 19 p.

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