






Advancing National Fire Danger Forecasting through Geoinformatics

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Abstract. With increasing climate variability, the risk of forest fires in northern Europe has risen substantially. Accurate, spatially explicit fire danger assessments are crucial for supporting operational decision-making by national authorities. Traditionally, Estonia has relied on the Nesterov index—a simplified fire danger metric derived from meteorological observations recorded at only 23 stations. However, this method offers limited spatial resolution and does not account for several key meteorological drivers. This paper presents the implementation of the Canadian Forest Fire Weather Index (FWI) system within the Estonian meteorological service, carried out under the RITA (2019–2020) state-commissioned research programme and the 2023–2032 EU LIFE-SIP AdaptEst project.

This development included high-resolution (1 × 1 km) raster-based FWI computation, adaptation of numerical weather prediction (NWP) model outputs for FWI inputs, statistical comparison between Nesterov and FWI indices, classification calibration using historical fire events, and the design of visualisation and web-based operational tools. The results showed strong statistical correspondence between the two indices (correlation coefficients of 0.7–0.8), while the FWI system offers greater temporal responsiveness, finer spatial resolution, and greater operational relevance. In addition, the paper outlines the consultation process between the involved parties to define fire hazard classes tailored to Estonian environmental conditions, as well as the implications of these definitions for future fire risk forecasting and risk management.

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Data and Software Availability. This paper does not contain directly associated data or software.

1 Introduction

Across Europe, the impacts of climate change have intensified concerns regarding vegetation and forest fire risks. Even in humid and temperate countries such as Estonia, prolonged droughts, early spring flammability, and increasingly frequent summer heatwaves have contributed to elevated fire potential. Landscape and forest fires pose risks not only to ecosystems but also to infrastructure, human health, and national security.

Accurate and spatially detailed fire danger information is essential for state authorities, particularly the Estonian Rescue Board, which is responsible for enforcing restrictions and allocating resources during high-risk periods. For decades, the Estonian Environment Agency (KAUR) produced daily fire danger maps based on the Nesterov index (Nesterov, 1949). Although operationally useful, this method relies solely on weather station measurements and does not adequately account for spatial variability or capture the complexity of fire–weather interactions.

To address these national needs, a coordinated scientific and technological effort was initiated to modernise Estonia’s fire danger modelling system. A key proposal emerging from the Geography Department of the University of Tartu (UT) during the RITA remote sensing project was to adopt the implementation FWI from the Canadian Wildland Fire Information System (NRCan,

2022; Stocks *et al.*, 1989; Van Wagner, 1974 and 1987), the FWI has become a globally recognised standard and is used by numerous national meteorological services (Kudláčková *et al.*, 2023) and environment applications, the European Forest Fire Information System (EFFIS) (Copernicus, 2019; EFFIS website), and the European Space Agency financed projects (Di Guisepe, 2023). Beginning in spring 2025, KAUR completed the transition to the FWI as the national operational method for fire danger assessment.

The present paper documents the scientific, geoinformatics, and methodological foundations of this transition, including the development of high resolution raster-based modelling workflows, the integration of diverse meteorological data streams, and the collaborative co-design of the operational system together with end-users.

2 Background

Although Estonia is not among Europe's most fire-prone regions, historical records reveal clear seasonal patterns in fire occurrence. Early-spring grass fires are most frequent before new vegetation begins to grow, when dead biomass dries rapidly under increasing solar radiation. In summer, fires typically occur during prolonged warm, dry periods, which increase fuel flammability and reduce moisture content. More intense fire events occasionally arise under extreme weather conditions, and interannual variability in fire danger is considerable. Climate projections indicate that drought episodes will become more frequent and temperatures will continue to rise, both of which are expected to increase future fire risk.

The long-used Nesterov (1949) index is based on a simple formula that combines air temperature, dew point (as a proxy for relative humidity), and previous day precipitation. The index is cumulative, increasing over prolonged dry periods. Although this approach is computationally efficient, an implementation based on only 23 meteorological stations has several major limitations. Its spatial coverage is sparse, and the method is highly sensitive to precipitation, yet rainfall occurring between stations is not captured and therefore cannot be incorporated into spatial interpolation. The calculation also omits wind, despite its well-known influence on both ignition probability and fire spread. Furthermore, the index has limited drought memory: a single rainy day can sharply reduce the value, failing to represent deeper or longer-term moisture deficits. Finally, there is an inherent temporal lag, because midday maps depend on meteorological observations from the previous day. These shortcomings have motivated the search for a more

physically grounded, internationally validated method for operational fire danger assessment.

The Canadian Forest Fire Weather Index (FWI), developed in the 1950s and subsequently validated across a wide range of ecosystem types, provides a comprehensive framework for assessing fire danger (Van Wagner, 1974; Van Wagner, 1987; Stocks *et al.*, 1989; NRCan, 2022). The system was derived empirically through extensive measurements of forest and grassland fuel responses to weather conditions (Alexander and De Groot, 1988). It incorporates multiple forms of precipitation accumulation across varying time scales and fuel categories, captures the day-to-day dynamics of temperature and humidity, and explicitly integrates wind speed to reflect its critical influence on ignition likelihood and fire spread (Stocks *et al.*, 1989; Lawson and Armitage, 2008). The methodology also includes several fuel moisture sub-indexes ('codes' in original documentation) that characterise the condition of fine surface fuels, deeper organic layers, coarse woody debris, and grassy vegetation affected by prolonged drought.

Beyond the improved formula for calculating fire danger, the newly implemented system introduces several additional—and arguably even more important—advancements. In the new methodology, high-resolution meteorological data are incorporated as a continuous raster field covering all of Estonia at a spatial resolution of 1×1 km. Precipitation fields are derived from weather radar, while temperature, humidity, and wind variables are obtained from numerical weather prediction (NWP) models, which are calibrated against weather station observations as needed.

This results in a dramatic increase in spatial detail: instead of relying on 23-point measurements, the system now operates on approximately 44,000 grid cells—roughly 2,000 times more spatial sampling. This level of detail matters. In the updated workflow, the composite FWI components are not interpolated from station data; rather, they are calculated independently for each raster pixel across the entire national domain. This shift enables a far more realistic representation of spatial variability in fire danger conditions, capturing previously undetected localised patterns.

3 Development steps and participating parties

3.1 Proof-of-concept phase

During the first proof-of-concept phase of the RITA project (RITA, 2020), the Department of Geography (UT) carried out a comparative analysis of the advantages and limitations of both fire-risk indexes and recommended

adopting the FWI to improve fire-safety forecasting. The Institute of Physics (UT) provided high-resolution meteorological data from weather models, along with an algorithm to adapt the data for the FWI calculation workflow, including rescaling and transforming into the project grid. The Tartu Observatory (UT) contributed by producing remotely sensed maps of fuel types—vegetation types prone to burning under dry, hot, and windy conditions. The Department of Geography team integrated all datasets and additional inputs into a single computational workflow. Maps for both indexes—Nesterov and FWI—were produced, and their sensitivity to various weather events and their ability to predict fire danger were analysed.

The maps and analytical results were presented to potential end users at the Rescue Board and the Weather Service, where they were discussed in detail. It became evident early on that continuous-value fire index maps are not suitable for operational decision-making, as the data require additional generalisation and scaling. One of the first questions raised by operational services concerned the relationship between the values of new index and the established danger classes. In their operational context, danger classes are directly linked to issuing warnings, imposing public restrictions, and activating response procedures—actions that are defined by law.

Initial approaches for deriving danger classes, as well as methods for generalising the data at county and municipal scales, were proposed and reviewed. The RITA project also examined the potential to model fire propagation; however, this component was not implemented in the project's later stages.

3.2 Implementation phase

In the second phase, the system was implemented through coordinated contributions from several institutions during the EU LIFE-SIP AdaptEst programme (2023–2032). The Department of Geography contributed to the development of the geoinformatics components, including algorithm design, spatial data processing, visualisation workflows, and classification analysis.

The Estonian Environment Agency (KAUR) and its Weather Service—the primary users of global and regional numerical weather prediction (NWP) models and operators of the national weather observation network, including weather radars—were responsible for establishing the data-handling workflow. Using NWP forecasts extended up to three days, it became possible to compute the expected development of the FWI over the same three-day period. All computational processes were ultimately deployed on KAUR's hardware infrastructure. The development work also addressed occasional failures in data chains, particularly for weather radar data, and

incorporated fallback algorithms that rely on weather station observations.

Complementing the components described above, the Information Technology Centre of the Ministry of Environment (KeMIT) provided the technical infrastructure and ensured the seamless integration of all modules into operational applications. A critical part of the implementation involved setting up two dedicated web services to deliver daily fire-danger maps to operational users and the public. These services were developed collaboratively by the KAUR and KeMIT.

The web services perform several coordinated functions. First, newly computed 1×1 km FWI grid data are automatically ingested into the GeoServer instances each day, ensuring that the most up-to-date meteorological inputs are reflected in the results. Next, geoinformatics tools clip, reproject, and resample the raster outputs, including refining them into 100×100 m visualisation layers. This enables high-quality map rendering even when users zoom into local details such as coastal zones or small inland communities. The service then generates interactive, user-friendly maps using OGC-compliant protocols, applying colour-coded hazard classes based on the established classification scheme. A comprehensive warning system for operational services, municipalities, and the public was also designed and implemented.

This setup was made possible by several important decisions made in collaboration among researchers, IT specialists, and end users. One of the most critical decisions concerned the selection of an appropriate classification scheme to convert the continuous-field FWI raster into discrete hazard classes. On the one hand, it was essential to consider how forecasters and rescue teams had previously interpreted hazard alerts, particularly during the transition from the older Nesterov index to the newer FWI system. On the other hand, the classification of potential risks needs to align with the severity categories used for actual fire events. Finally, we aimed to develop a classification system that would, at least to some extent, be comparable to the danger classifications used in neighbouring countries.

One important consideration was preserving the familiar meaning of low, medium, and high fire danger levels as understood by society. A straightforward mathematical recalculation from one index to another was not possible because of the conceptual differences behind their calculations. To address this, we conducted a statistical comparison of the FWI and the Nesterov index, calculated over the same time period. The results showed strong correlations (0.7–0.8), confirming contextual consistency while also revealing that FWI is more sensitive to meteorological variability, particularly wind.

We also tested and compared multiple classification schemes used in different systems (e.g., EFFIS, SMHI (SMHI), CWFIS and the historical Canadian FWI D-scale (CWFIS)) and developed a custom scale suitable for Estonia. In addition, we analysed how well the index agreed with historical fire events to align the FWI-based classification with observed fire occurrence patterns. For this, we analysed the development of FWI near and before the events, stored in the Rescue Board databases for years 2023 and 2024. It should be noted that weather-related fire danger is not the sole factor influencing fire ignition; human presence and activities play a major role. Nevertheless, the analysis showed that higher FWI values strongly correlate with a higher likelihood of fire ignition and the severity of the event.

Two rounds of consultations were held with the Estonian Rescue Board and KAUR forecasters to evaluate map readability, the usefulness of the proposed hazard classes, operational implications, and consistency with historical fire events. Based on these discussions, the fire danger classes were further refined.

3.3 Lessons learned

The development of this project has been an uncommon experience for the research team. Although the first phase was conducted as an applied science initiative, it nevertheless allowed for substantial academic freedom. The subsequent practical integration of the proposed methods into the daily workflow of an official weather forecasting system—which also served as the basis for administrative fire-hazard warnings—maintained the scientific responsibility of the work but introduced several new practical considerations.

When collaborating with state institutions or public services, researchers may encounter several notable differences compared with typical academic research environments. First, the pace of project development tends to be slower, more structured, and less flexible. This is largely due to the need to comply with legal and regulatory frameworks. Delivering results in this context entails not only scientific validation but also clear implications for operational response actions and the issuance of legally binding public restrictions.

3.4 Stakeholders' complexity.

Stakeholder complexity is another defining characteristic of collaboration with state services. Unlike academia, such projects involve a wide range of actors—senior decision-makers, legal and IT/security experts, project managers, and domain specialists—each with different priorities. This diversity requires communicating research in multiple formats. In our case, much of this groundwork

was completed during the first project phase, as most end-users and partners were already involved. This continuity ensured a smooth workflow and prevented major issues.

The administrative documentation required by state agencies was largely prepared by our governmental partners, while the academic team contributed mainly scientific comments and revisions. Two factors further facilitated the process: the participants from both sides had established working relationships beforehand, and communication within Estonian public institutions tends to be relatively informal and efficient. Together, these conditions helped maintain a fluent and productive collaboration.

4 Conclusions

This project demonstrates how geoinformatics is reshaping fire-weather operations. Grid-based modelling replaces point interpolation methods, and web platforms deliver near-real-time, high resolution outputs. This methodological shift follows broader international trends in environmental monitoring. Also, the power of forecasting in NWP models enabled early warning products for FWI. Advantage of FWI over legacy methods is that it integrates wind—critical in Estonia's coastal climate—and incorporates drought memory, preventing unrealistically rapid drops in fire danger. All of these enabled the establishment of a modern, internationally aligned wildfire danger monitoring infrastructure.

However, FWI thresholds used in Mediterranean or boreal ecosystems are not directly transferable to Estonia. Joint analysis with local fire event data confirmed the need for national thresholds to avoid both overwarning and underwarning. The full operational transition to FWI by spring 2025 showed strong performance during the 2025 season, providing a robust basis for future climate adaptation and fire risk management.

Next steps should include integrating remote sensing fuel moisture mapping and applying fire behaviour models (e.g., rate of spread, flame length) to support operational response. Long-term climatological FWI trend analysis also becomes feasible for further academic research.

Declaration of Generative AI in writing

The authors declare that they have used AI tools in the preparation of this manuscript for language editing, to improve grammar and sentence structure, but not for generating scientific content, research data, or substantive conclusions.

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