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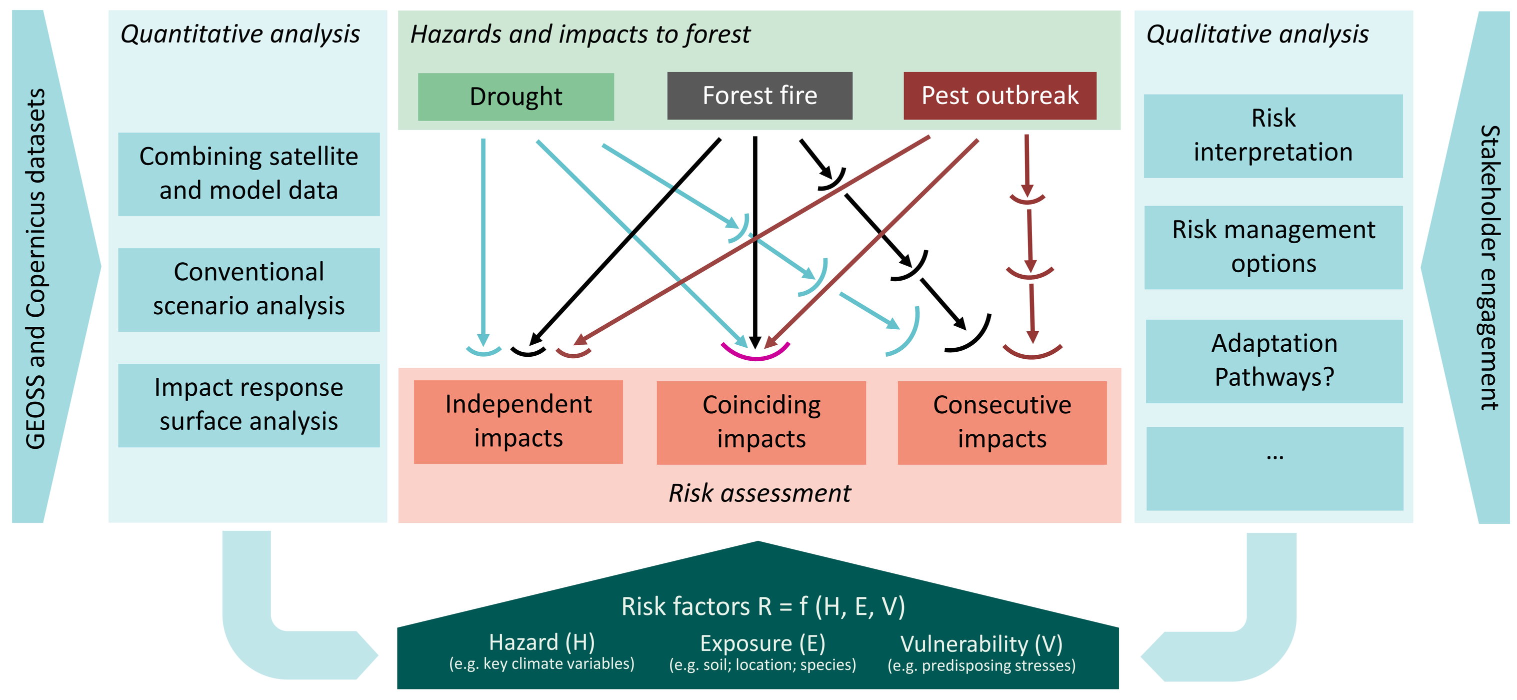


**Figure 1. Multi-hazard framework for climate-related risks to forests.**

# Towards a multi-hazard risk assessment for forest disturbances in Finland

**Finland is affected by climate warming that occurs more rapidly at higher latitudes compared to the global mean and increases the risks of multiple hazards in forests. We present a multi-hazard framework with focus on three hazards: drought, forest fires and forest pests (Figure 1).**

## Methods

### 1. Analysis of droughts

Droughts were assessed using a new version of the Watershed Simulation and Forecasting System (WSFS-P) from the Finnish Environment Institute (Syke). The WSFS-P was developed to produce sub-seasonal drought forecasts based on standardized drought indices and using European Centre for Medium-Range Weather Forecasts (ECMWF) products as input. Soil moisture observations from the Soil Moisture and Ocean Salinity (SMOS) mission were used in the evaluation of simulated soil moisture.

### 2. Analysis of forest fires

The Canadian Fire Weather Index (FWI) was applied to construct impact response surfaces combined with Coupled Model Intercomparison Project Phase 6 (CMIP6)-based probabilistic projections of climate change (Fronzek et al. 2022).

### 3. Pest outbreak predictions

Selected moth pest species observations were extracted from the Finnish moth monitoring scheme (Nocturna). Species with similar foraging behaviour were grouped and mass occurrences were modelled with logistic regression models using climate variables and satellite-observed green-up dates from Moderate Resolution Imaging Spectrometer (MODIS) data (Böttcher et al. 2018) as explanatory variables.

### 4. First steps on multi-hazard analysis

The correlation between different drought indices and drought and fire danger indicators and the normalized difference water index (NDWI) from MODIS was analysed.

First attempts were made to identify coinciding hazard events for drought and forest fire from time-series of daily estimates of discharge soil moisture and FWI and to combine individual risk maps.

## Results and conclusions

1. The new version of the national-scale hydrological model was validated with SMOS soil moisture (**Figure 2**), discharge and water level data. WSFS-P can be utilized to estimate and forecast meteorological, agricultural and hydrological droughts (**Figure 3**).

2. Impact response surfaces combined with probabilistic projections of climate change allow to quantify the likelihood of exceeding critical impact thresholds of fire danger (**Figure 4**). Further work will extend the analysis with the FWI to incorporate fuel load information and apply the approach also to droughts and pest risks.

3. Climate variables explained well variations in moth mass occurrences, with differences for species groups. Drought was an important variable to predict mass occurrences. Satellite-observed green-up was significant to predict the mass occurrences of moth species foraging on deciduous trees.

4. Clear interconnection of drought and fire danger indicators were found, but choice of indicator matters in defining the risks. Combined risk maps (**Figure 5**) are experimental. They provide basis for stakeholder discussions and will be elaborated further including drought and fire risks.

Our results contribute to understanding of climate-related multi-hazard risks for forests in Finland and support their governance.

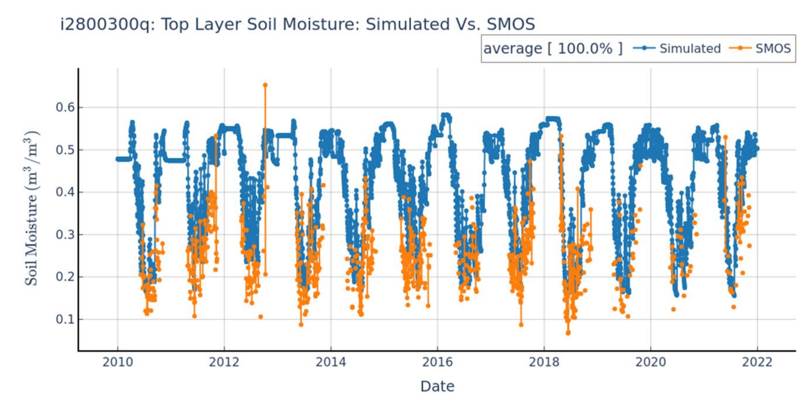


**Figure 2. The average soil moisture data above the Hypöistenkoski discharge observation point in the Aurajoki watershed (South-West Finland), derived from Watershed Simulation and Forecasting System (WSFS-P) simulations and SMOS soil moisture observations. SMOS soil moisture compared reasonably well to simulated soil moisture for the top 10 cm soil depth, however values were consistently lower than soil moisture simulated by WSFS-P.**

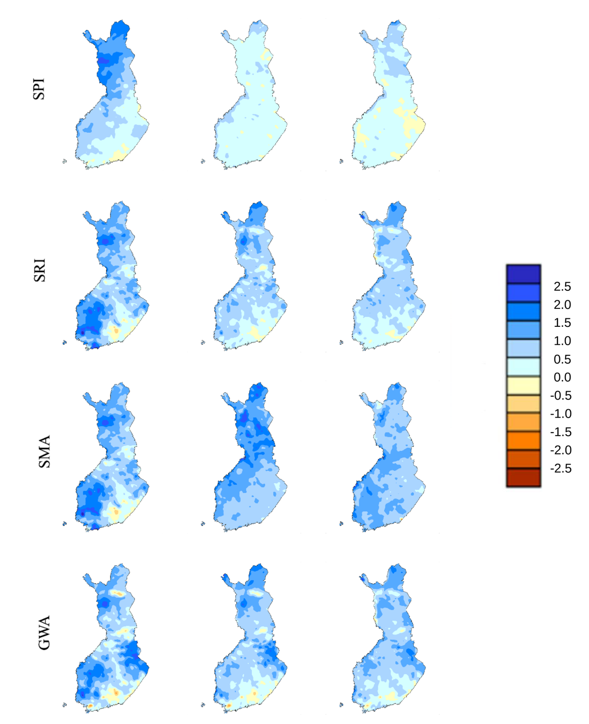


**Figure 3. Drought forecast maps for September (left column), October (middle) and November (right) based on Standardized Precipitation Index (SPI), Standardized Runoff Index (SRI), Soil Moisture Anomaly (SMA) and Groundwater Anomaly (GWA) (rows). The drought forecasts are produced twice a week for the current month and two following months.**

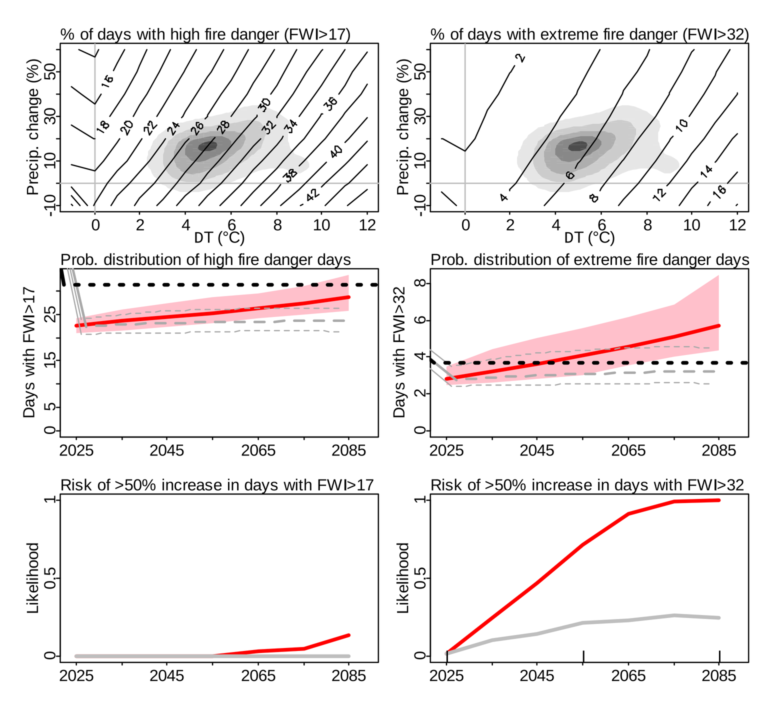


**Figure 4. Probabilistic assessment of high (left) and extreme (right) fire danger in Helsinki (South Finland). Top row: Impact response surfaces of fire danger days (black contour lines) and probabilistic projection of climate (grey shading – CMIP6, SSP5-85, 2071-2100 wrt. 1991-2020), middle row: probabilistic distribution of fire danger days shown as median (solid lines) and 5–95 % range (shading); bottom row: likelihoods of exceeding a threshold 50% increase in fire danger days wrt. to the baseline 1991-2020.**

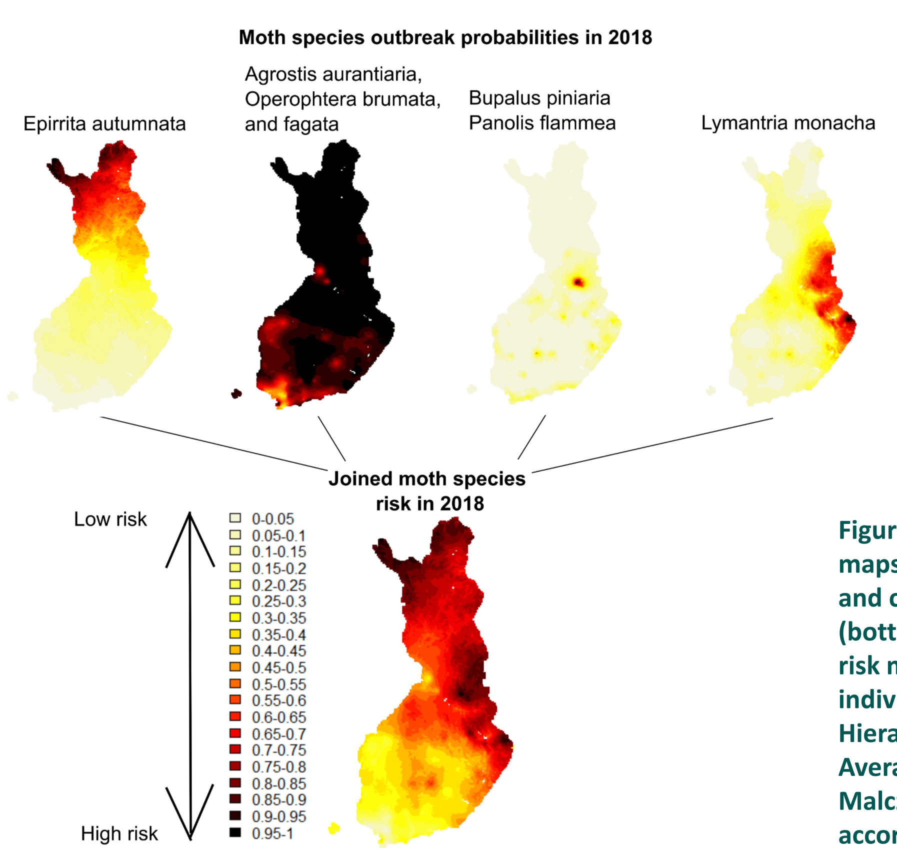


**Figure 5. Preliminary moth outbreak risk maps for individual species groups (top) and combined risk map for all species (bottom) for a dry year 2018. Combined risk maps were calculated from fuzzified individual risks and by using the Analytical Hierarchy Process and Ordered Weighted Averaging (Yager 1988, Boroushaki and Malczewski (2008). Weights were given according to past outbreaks.**

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