PIISA

Piloting Innovative Insurance Solutions for Adaptation

D3.13: Pilots for Forests

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Keywords

Climate-resilience, parametric insurance, climate adaptation, forest risk management, wildfires, windstorms, Portugal, Germany

Abbreviations and Definitions

Acronym	Description
AGIF	Integrated Rural Fire Management Agency of Portugal(Agência para a Gestão Integrada de Fogos Rurais)
AOI	Area of Interest
CCDRC	Central Regional Coordination and Development Commission of Portugal
CMCC	Euro-Mediterranean Center on Climate Change (Centro euro-Mediterraneo sui Cambiamenti Climatici)
CWS	Critical Wind Speed
EU	European Union
FBP	Fire Behavior Prediction
FMI	Finnish Meteorological Institute
FWI	Fire Weather Index

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GA	Grant Agreement
ICNF	Portuguese Institute for Nature Conservation and Forests (Instituto da Conservação da Natureza e das Florestas)
MTT	Minimum Travel Time
NAP	National Adaptation Plan
OPF	Forest Producers Organization
PIISA	Piloting Innovative Insurance Solutions for Adaptation
RoL	Rate on Line
SWI	Storm Weather Index
TRL	Technical Readiness Levels
USDA	United States Department of Agriculture
WISE	Wildfire Intelligence and Simulation Engine
WP	Work Package
WPEI	Wind Power Exposure Index
WTP	Willingness to Pay
ZIF	Forest Intervention Zone

Table 1: List of acronyms and their descriptions

Some key insurance terms that are used in this report across the two pilots are defined in Table 2.

Term	Meaning
TIV	Total Insured Value; total value covered by the insurance program
Deductible	Part of the risk retained by the insuree and deducted from the insurance payout.
Gross loss	‘Pure’ loss estimated per event
Net loss	Gross loss minus the deductible
Exit / limit	Maximum payout for the insurance
Expected Loss (EL)	Loss modelled by the insurer per year
Loadings	Corresponds to the additional charges added to the EL to cover the risk volatility, commercial expenditure, brokerage fees, etc.
Premium	What the insuree pays the insurer $Premium = EL * loadings = \min(\max(Gross\ loss - deductible, 0), limit)$
Rate on Line (RoL)	Ratio between the premium and the maximum payout or limit

Table 2: Definitions of key terms used in insurance

Executive Summary

Climate change is intensifying systemic risks to European forests, with increasingly severe windstorms in Central and Northern Europe and recurrent, high-intensity wildfires in Mediterranean regions. These hazards threaten not only forest ecosystems and livelihoods, but also national economies, public finances, and the long-term carbon sequestration capacity of forests. Despite the growing scale and frequency of these risks, insurance coverage and penetration in the forestry sector remains structurally low across Europe, leaving a significant protection gap and limiting the financial resilience of forest owners and affected communities.

The Piloting Innovative Insurance Solutions for Adaptation (PIISA) project is a three-year initiative bringing together 12 partners from 5 EU countries, including research institutions, insurance experts, universities, and meteorological agencies. PIISA aims to explore how climate services, advanced hazard modelling, and innovative insurance design can better reflect climate risks and adaptation efforts, and thereby support climate adaptation while improving the insurability of climate-exposed assets. A core principle of the project is co-development and co-creation, with stakeholders actively involved throughout the design, development, and validation of the proposed solutions.

Within PIISA, AXA Climate leads two forestry pilots under Work Package 3, targeting two of the **most critical climate-driven risks to European forests: windthrow and wildfire.** This deliverable documents the development pathways of both pilots, synthesizes previously published work, and presents new modelling results and insights generated during the later development cycles of the pilots.

The first pilot on windthrow risks focused on integrating forest vulnerability into insurance modelling. The pilot **integrated detailed forest characteristics (such as species composition and stand structure) into a forest vulnerability map, and developed a Wind Power Exposure Index taking wind speed, wind direction, and storm duration into account.** Together, these two components enable **the estimation of expected storm damages at a forest-stand level, and support insurance product development and pricing.** Initially developed and tested in Germany, the modelling framework was subsequently validated across several European countries, including France, Ireland, Scotland, and Denmark. Indicative insurance pricing simulations based on the model outputs resulted in a premium of approximately 5€ per hectare per year for an insured value of 1,000€ per hectare, broadly aligned with observed willingness-to-pay levels for forest insurance in Europe. The pilot demonstrates that **wind risk can be quantified in a scalable and replicable way**, while highlighting the importance of regional calibration and ground-truth validation prior to product deployment.

The second pilot on wildfire risks focused on **integration adaptation measures into wildfire risk assessment and insurance design.** Conducted in Central Portugal, the pilot combined wildfire hazard modelling with adaptation scenarios derived from national and regional fire management

plans developed by the Agency for Integrated Rural Fire Management (AGIF). Two complementary fire spread models were calibrated using historical fire data and satellite observations, and used to simulate baseline and adaptation scenarios involving primary and secondary fuel management networks. Results show that well-designed and properly maintained fuel management measures can **reduce annual burn probabilities by approximately 30–40%**, whereas poorly maintained or degraded measures yield risk reductions of only around 5%. When translated into insurance pricing, fully implemented adaptation scenarios resulted in substantial premium reductions—**up to 70–95% for forest coverage and 80–84% for building exposure**, depending on the model and insurance structure utilized. Primary fuel breaks were identified as the main driver of premium reduction for forests, while secondary fuel breaks played a dominant role in reducing risk for buildings and settlements. Beyond premium effects, adaptation measures also enabled more favorable insurance conditions, such as lower deductibles and higher coverage limits, supporting continued insurability under worsening fire-prone climate conditions.

Taken together, the two pilots demonstrate that climate risks to forests can be quantified in ways that is operationally meaningful for insurance and risk management, and that adaptation measures, when properly modelled, can generate measurable risk reduction and enable significant premium differentiation. They also showcase that insurance and adaptation are not necessarily substitutes; rather, they are complementary tools that can jointly enhance climate resilience. Key conditions for scaling such solutions were also underlined, including the need for high-resolution climate services, robust regional calibration, territorial aggregation of risks, and strong alignment with public-sector adaptation policies. While the modelling architectures developed under PIISA are replicable and transferable across Europe, successful replication and deployment will depend on sustained stakeholder engagement, institutional coordination, and careful adaptation to local ecological and governance contexts. This work provides a strong foundation for scaling adaptation-linked insurance innovation across Europe. By demonstrating how climate risks and adaptation measures can be jointly modelled and translated into actionable insurance solutions, it supports more resilient forest management and investment decisions. In doing so, it contributes directly to strengthening the EU's climate resilience objectives and reducing the climate-related insurance protection gap.

1 Introduction

European forests are increasingly exposed to climate-driven disturbances that challenge their ecological integrity and economic viability. Windstorms, prolonged droughts, bark beetle outbreaks, and wildfires are becoming more frequent and more severe. These disturbances not only generate direct financial losses but also undermine biodiversity, ecosystem services, and carbon storage.

Considerable progress has been made in planning for climate adaptation and implementing related policies in Europe. However, the recent European Environment Agency review of national climate adaptation actions highlights that implementation of adaptation needs to be significantly strengthened (Leitner, Johnson, et al., 2024). There are common barriers to actions effectively addressing climate risks such as lack of risk awareness. Also, there is a need for new and alternative ways to design insurance policies, which could help stimulate the uptake of climate insurance while addressing affordability and risk-reduction objectives (Ceolotto, et al., 2024).

At the same time, the forestry sector faces a persistent protection gap. Insurance products are often unavailable, insufficiently tailored to forest management realities, or perceived as unaffordable. Where coverage exists, it may not adequately support resilient recovery actions such as replanting or long-term stand management. This misalignment weakens incentives for proactive adaptation and limits the role insurance could play as a climate resilience tool.

PIISA (Piloting Innovative Insurance Solutions for Adaptation) is a Horizon Europe funded project working to reduce the climate change adaptation gap (i.e. the difference between the recognized need for adaptation and the implemented adaptation) and insurance protection gap (i.e. the different between the amount of insurance that is economically beneficial and the amount of coverage actually purchased) by developing and piloting new insurance and risk-sharing concepts to address mounting climate risks in Europe. The central premise is that improved risk modelling combined with stakeholder co-design and adaptation-sensitive insurance structures can enhance insurability, incentivize prevention, and strengthen financial resilience.

The PIISA project seeks to extend, where possible, insurance from purely compensatory, post-damage mechanisms to proactive instruments that incentivize policyholders, communities, and public authorities to adopt climate change adaptation measures e.g. via premium discounts. Recognizing that innovative insurance solutions and risk awareness raising have roles to play in helping EU Member States strengthen their climate adaptation efforts, PIISA has developed and tested a range of insurance related innovations that have been co-created to enable and stimulate households, firms, and public sector organizations to manage climate risks and adapt.

Within this framework, this deliverable focuses on the two forest pilots under WP3 to address key climate-driven risks that increasingly threaten European forests i.e. windthrow and wildfire risks. These pilots aim to develop, test, and demonstrate innovative insurance solutions and climate services that support adaptation, reduce vulnerability, and bridge existing protection gaps. The windthrow risk was addressed through the development of a scalable modelling framework integrating wind hazard and exposure data, and vulnerability characteristics, to develop a wind power exposure index for insurance innovation. Piloting started with co-design with stakeholders in Germany (Task 3.4.1). The wildfire risk included the integration of adaptation measures – specifically fuel management networks – into hazard modelling, allowing burn probability reductions to be explicitly quantified and linked to indicative insurance pricing in Portugal (Task 3.4.2).

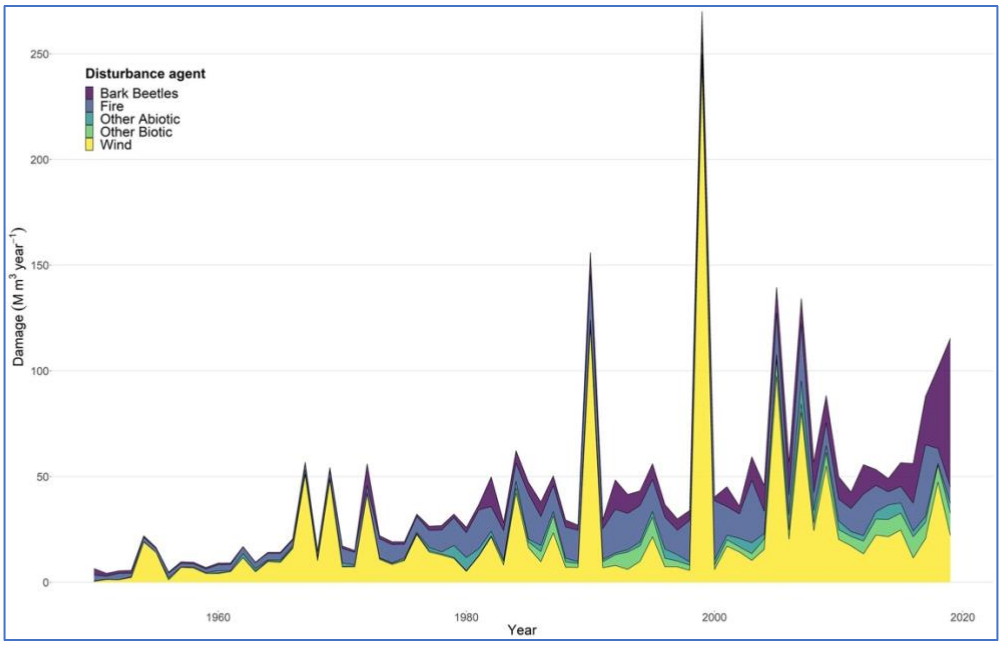
Together, these pilots test the hypothesis that adaptation can be made financially viable within insurance systems and that climate services can support more informed underwriting and forest management decisions. This deliverable synthesizes the full piloting process for each pilot, summarizing co-creation processes with stakeholders, modelling developments, results, awareness-raising efforts, and final recommendations and next steps for enhancing adaptation through insurance.

2 Pilot 1: Windthrow risks for Forests

2.1 Motivations and objectives of the pilot

European forests are increasingly exposed to the consequences of climate change: extreme windstorms, wildfire, droughts, and other disturbances such as snow and pest outbreaks. Despite this growing hazard, forest insurance remains marginal – for instance, only a small fraction (1-5%) of Germany's forest area is insured, leaving many forest owners financially vulnerable (Gardiner, Blennow, et al., 2010). This underinsurance stems from low awareness of natural-capital asset insurance, limited availability of tailored insurance products, lack of awareness of increasing climate risks, and a mismatch between perceived and actual risk (Kochar, Voituron, et al., 2024). As climate change intensifies, these vulnerabilities threaten not only the economic viability of private forestry but also the long-term resilience and sustainability of forest ecosystems.

To respond to this protection gap, this forest pilot under the PIISA project aims to design, test, and develop an innovative, climate-sensitive insurance solution for windthrow risks informed by high-resolution climate and forest modelling, integrating hazard modelling, stand-level vulnerability assessment, and actuarial pricing. The pilot started with a first location in Germany and initially explored multiple perils, but due to the magnitude of windthrow risk (causing 50% of all forest loss in Europe between 1950 and 2019 as shown in Figure 1 [Patacca, Schelhaas, et al., 2020]) and the availability of robust datasets, the scope was strategically reduced to focus on windstorms only.



Source: Patacca, Schelhaas, et al., 2020

Figure 1: Total reported damage caused by natural disturbances in Europe between 1950 and 2019[1]

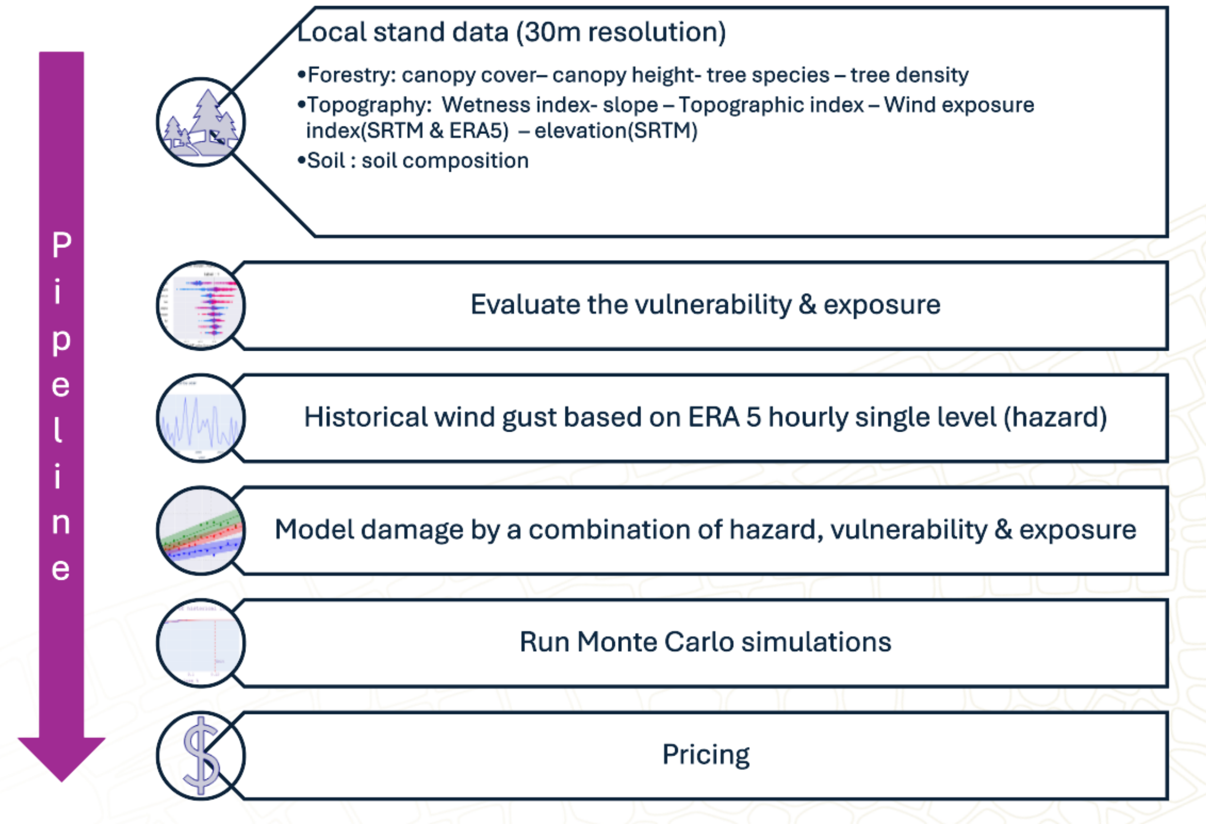
By doing so, the pilot seeks to create an insurance product that reflects real climatic and forest risks, supports adaptive forest management, and provides forest owners with credible, affordable coverage against windstorm damage. It further validates product feasibility and replicability by working closely with forest owners and a commercial partner (AXA Germany), as well as expanding the scope beyond Germany to test the product feasibility in other European regions and countries. The ultimate goal is to build a scalable, replicable mechanism for de-risking forestry investments across Europe.

2.2 Development cycles and methods

When looking at the overall structure, the pilot followed the iterative development logic of PIISA, progressing through design, co-creation, modelling, and refinement over three loops (development cycles). Each loop built on the previous one, allowing the pilot to incorporate stakeholder feedback, improve model performance, and converge towards an operational insurance prototype. Methods combined climate science, forest risk modelling, actuarial techniques, and stakeholder engagement. Data flows and model outputs were coordinated with WP2 to ensure consistency and benefit from climate services, indices, and mapping resources.

Figure 2 provides a visual overview of the entire co-development methodology and process for this pilot.

[1] https://doi.org/10.1111/gcb.16531



Source: AXA Climate

Figure 2: Overview of the process of co-development

2.2.1 Summary of work conducted and previously published in September 2024 (Loop 1: Design of Instruments; November 2023-August 2024)

Loop 1 of this project focused on creating a climate-sensitive forest insurance product in Germany in close collaboration with AXA Germany and forest owner Forst Arco Zinneberg. This work is documented in published PIISA Deliverable 3.9: Concept of Climate Change Risk Sensitized Forest Insurances (Kochar, Voituron, et al., 2024). The initial phase of the pilot established its background and motivation while building strong partnerships with forest owners, insurers, and technical experts. Through six structured co-design workshops, the team scoped priority risks and developed early conceptual models for multi-peril coverage, addressing abiotic and biotic threats including windthrow, wildfire, snow, and bark beetle risks. This phase included preliminary data gathering and evaluation, followed by the development of a comprehensive database covering forest and soil characteristics, topography, and wind-related variables. In parallel, a wind hazard model was developed in collaboration with Amigo, exploring the viability of their Standardized Windstorm Index (SWI) for insurance design, and the first steps toward a vulnerability mapping framework were initiated. Insurance pricing approaches were also explored, with AXA Climate assessing parametric structures and AXA Germany evaluating indemnity-based solutions for windthrow and wildfire risks for the Arco-Zinneberg forest.

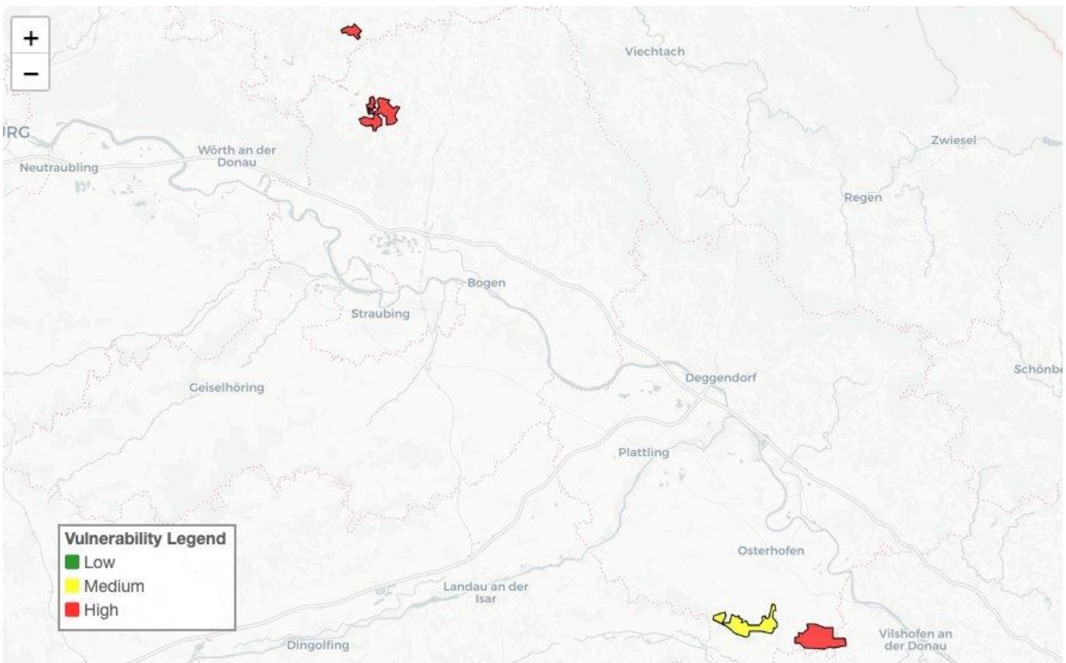
During this loop, the initial ambition to develop a multi-peril insurance model was assessed. Discussions with the AXA Germany, combined with hazard statistics, indicated that windthrow represents by far the largest and most insurable risk in the German and western European context. For feasibility, modelling accuracy, and pricing stability, the scope was therefore reduced to windthrow only, which is what the remaining loops and thus the remainder of this report will focus on.

This methodological groundwork established in D3.9 now enables the pilot to move forward into Loops 2 and 3 with a refined scope and more mature models. The present deliverable therefore reports in more detail on the results from final model development, validation, pricing refinement, and stakeholder engagement focused on windstorm coverage.

2.2.2. Remainder of Loop 1 (September 2024-January 2025)

The remainder of loop 1 focused on consolidating the proof-of-concept work completed in the previous phase, and advancing toward a functional, exploitable windstorm insurance model.

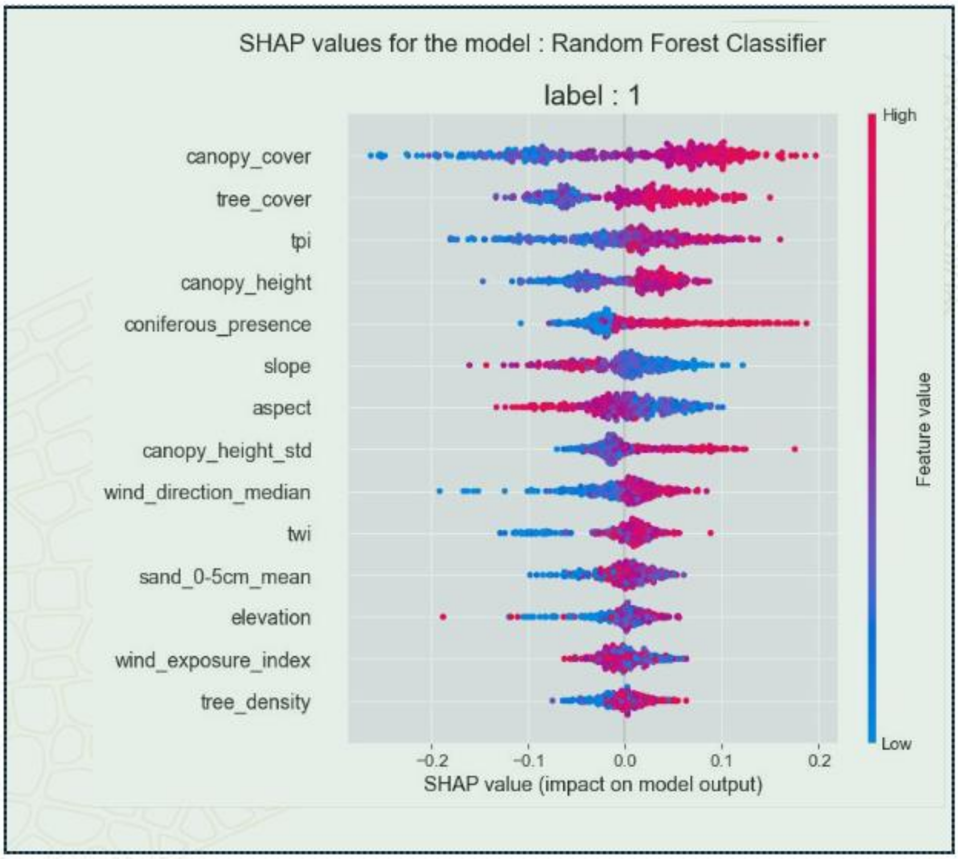
This process commenced with the vulnerability model development and refinement. Figure 3 shows the vulnerability maps developed for the pilot area. The modelling approach evolved from continuous regression-based vulnerability functions to a category-based model, where forest vulnerability is categorized using stand characteristics. Various characteristics like canopy height, cover, tree density, elevation, wind exposure, slope, etc. were incorporated into the vulnerability model design to understand factors driving forest vulnerability. These categories were refined using machine-learning clustering techniques, and will be further tested in additional areas, with the model design allowing for rapid updates based on the availability of client-specific data.



Source: AXA Climate

Figure 3: Categorical vulnerability maps for the pilot area

The model was trained in France, with different categories providing various levels of explanation, as shown in Figure 4. It was optimized to reduce basis risk and showed a relative error of 1.2% in the rest results, wherein the predicted damage was 2745.5 ha, while the true damage was 2780 ha.



Source: AXA Climate

Figure 4: Stand vulnerability characteristics and impacts on the model

The hazard data and gust speed were then validated. Wind gust speeds were initially calculated using maximum windspeeds from ERA5 and multiplying it by a conservative gust factor of 3 (wind-to-gust ratio approach (x3)), which were then compared with real gust speed observations from ERA5 reanalysis data (Copernicus Climate Change Service), showcasing good approximations between the historical speeds.

The damaged gust speed and vulnerability characteristics were then combined and simulated 10,000 times to generate pricing simulations (with model damage methodology inspired by Zeppenfeld at al., 2023). The direct gust data produced a lower risk profile than the gust speed factor values (gust ratio of x3), and therefore had more attractive pricing in the parametric product simulations across various scenarios. The premium levels were similar to those provided for indemnity products by AXA Germany, but indemnity products remained more competitive for the same coverage with lower deductibles and no limits (compared to parametric products with high deductibles and limits of 10-15%), despite having slower payout processes. Furthermore, low premium levels (~1.5% Rate on Line [RoL]) are not sufficiently attractive for parametric insurers, further reducing the likelihood of such a product reaching the market. Parametric windthrow products are therefore not likely to be suitable for low-risk areas of a relatively small size (2000 ha).

A hybrid solution was proposed to incorporate pricing based on the parametric index but loss assessment with the change detection model to bridge the gap between the models and product feasibility.

2.2.3. Loop 2: Test of applicability (January 2025-February 2026)

Loop 2 expanded the modelling beyond the initial pilot region, and focused on testing its transferability in new contexts with available storm data. The vulnerability model and forest management layers were previously completed for the pilot area, using publicly available data to ensure affordability and replicability.

Rather than pre-defining a second country, Loop 2 adopted an opportunistic approach with respect to data acquisition and validation. Wherever reliable storm data became available, the model was tested to assess stability and scaling potential.

<u>Vulnerability Model Validation and Replicability Testing in Ireland:</u>

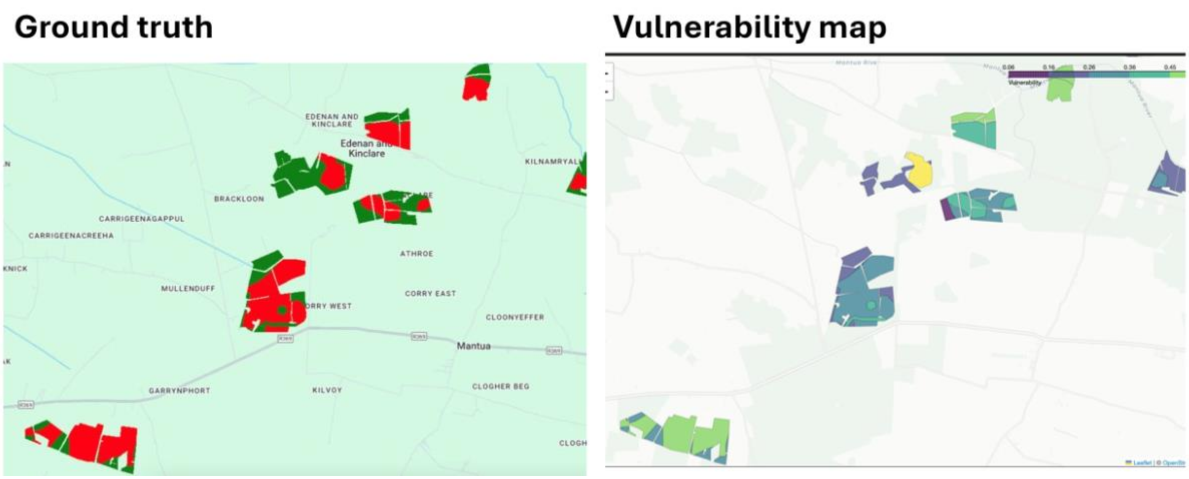
Additional storm-damage datasets were obtained from Ireland for the Eowyn storm, which occurred between 21st and 27th January 2025, including shapefiles of damaged and non-damaged areas and tree species, enabling validation in a different context (Atlantic biogeographical region, and land use and forest management practices).

Step I: Focus on vulnerability and exposure

- A database of 229 polygons was assembled, covering over 5600ha in area, of which over 1300ha were classified as damaged (54 polygons).
- When comparing the ground truth data with the vulnerability map layers (Figure 5), the map showed a good correlation with the actual damage, providing confidence in the map layers.
- With an optimal threshold of 31%, it was estimated that the vulnerability, as a continuous value, could explain 63% of the variance in the damaged area.
- To further test the robustness of the vulnerability mapping, the vulnerability was tested on both damaged and non-damaged areas, with a strong statistical difference observed (p-value= 0.0018). For interpretation ease, this implies that the values observed for damaged and non-damaged areas would be identical expected values only 0.18% of the time,

thereby showcasing statistically significant differences in vulnerabilities between damaged and non-damaged areas.

- Studying the different numbers of clusters, it was further validated that having three thresholds or categories of vulnerability (high, medium, low) as done previously was a good rule of thumb.
- Further robustness checks showed that the differences between the three categories are very strong, with highly vulnerable forests suffering 6 times more damage than low vulnerability forests, and medium vulnerable forests suffering 4 times more damage when compared to low vulnerability forests. This different was shown to be statistically significant (p-value < 0.001).



Source: AXA Climate

Figure 5: Comparison between ground truth data and vulnerability map outputs

Step II: Focus on vulnerability and hazard sensitivity

- Historical gust records were retrieved to build the dataset from the Irish Meteorological Service (Met Éireann)[2]. This data was collected across 12 locations in Ireland, including data points on wind characteristics including mean, highest gust speed, direction, etc.
- The local meteorological station data was then converted to align with global ERA5 land data. The average ratio of high gust and maximum wind speed was estimated at 1.6, which is similar to the one used from ERA5 land, as well as consistent with the factor used for the Arco Zinneberg pilot pricing (1.5 multiplier). This provided confidence in the preliminary figures, indicating toward a good potential for scalability as wind speed is easier to use for interpretation and pricing purposes. However, there was a bias noticed as a third of the observations was noted to have the same high gust estimates.
- Observations were created to build out the dataset, by a process of collecting points in a buffer region of 10 km across each location, computing zonal statistics for each buffer region, filtering the points with more than 90% of forest area, applying the vulnerability algorithm to attribute a value, and categorizing the vulnerability. It is important to note at this stage that while in the testing phase in-situ data was used, the damaged area at this

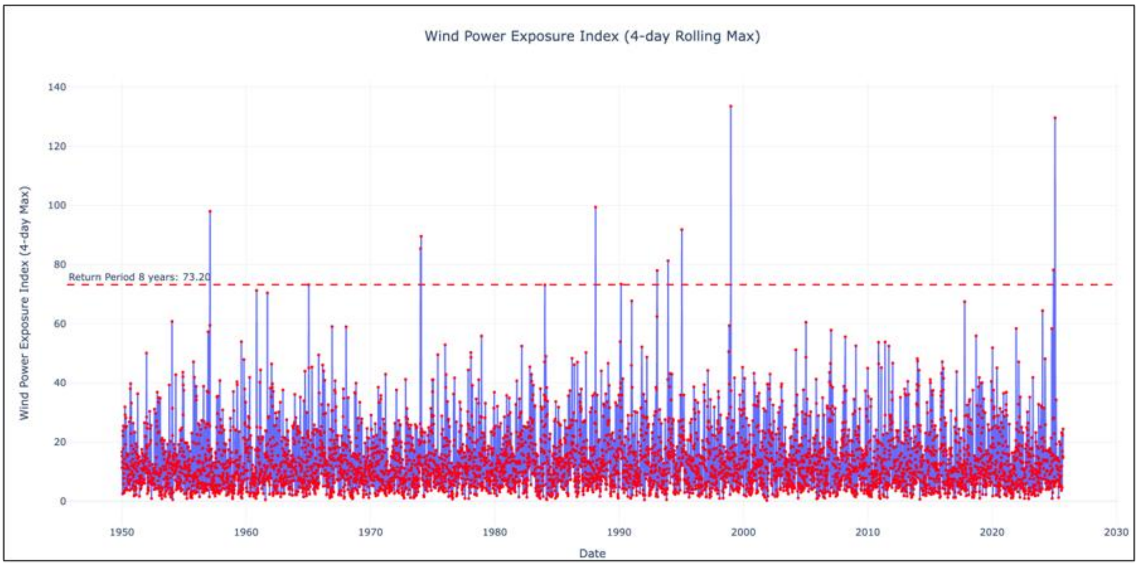
[2] https://www.met.ie/climate/available-data/historical-data

point has been modelized, taking harvested area (approximately 1.25% on average) into account as well.

- The final dataset consisted of 4385 forest data points, with 42 features, including vulnerability, damage percentages, and wind records. This is much more robust than the previous study which had 54 data points.
- The damage information was then categorized and clustered into different vulnerability classes (low, medium, high). This was done with different thresholds than the previous categorization exercise, since low vulnerability has different implications in France and Ireland, implying as well that certain local calibration work needs to be conducted for replication and scaling.
- Damage function output results were studied to understand the percentage of forests affected by gust speeds and vulnerability by category. The trend showed that for the most part, higher vulnerability was associated with higher damage, with the exception of some cases (~15%), which required further investigation and sensitivity analyses.
- The hypothesis that there might be a multiple storms compounding factor was then studied by filtering the dataset to stations exposed to one storm and studying the stand condition and typical critical wind speed (CWS). The filtered model explained the damage linked to the vulnerability better than when studying all the stations, but the first damage function still showed the same pattern i.e. the model doesn't correlate with the damage beyond the value of the highest CWS. These results are therefore not explained by the compounding effect of multiple storms.

Step III: Development of a new index for windthrow parametric structures

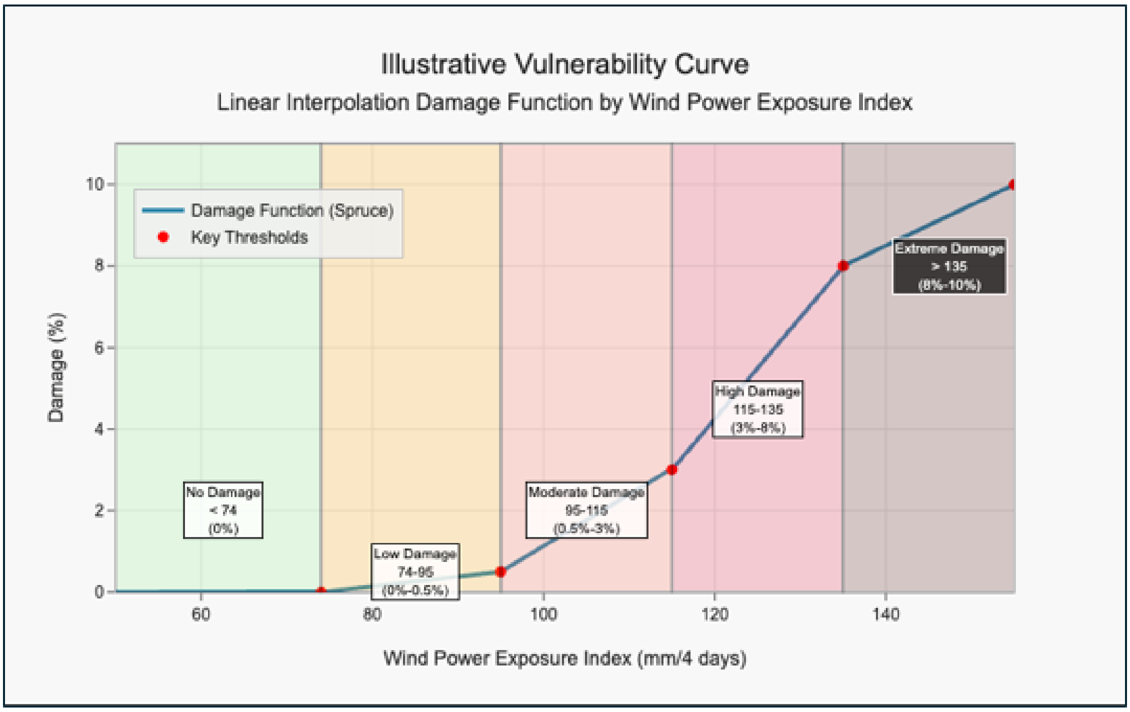
- Rationale: AXA Climate clients communicated that they were suffering greater damages than would be expected due to the wind speed. Given that changing tree resilience against prevailing wind direction is a well-established fact, the goal was to integrate information on the wind direction into the hazard modelling.
- Copernicus Services data was used to ensure robust, resilient, and transparent sources of data, using ERA5 land, and hourly aggregated, ECMWF Climate Reanalysis data at approximately 11 km resolution incorporating hourly wind speed and wind direction data, which was then tuned with different vulnerability layers.
- Creation of the Wind power Exposure Index (WPEI) (Figure 6), incorporating hundreds of thousands of data source inputs, following an 8-step process, taking into account physical power of wind, dominant wind direction, vulnerability, storm duration, and standard duration event.
- Dataset compilation: 27000+ data points as historical values of WPEI after filtering the final index, which can be used to calibrate return periods with client risk appetites. When tested in Scotland and Ireland, it was found to be consistent with local observations, providing confidence in the model. The return period can be utilized as a level to define the insurance trigger value to help clients project themselves onto events that want to be covered for, using it as a strong level of price sensitivity.



Source: AXA Climate

Figure 6: Visual Overview of the Wind Power Exposure Index

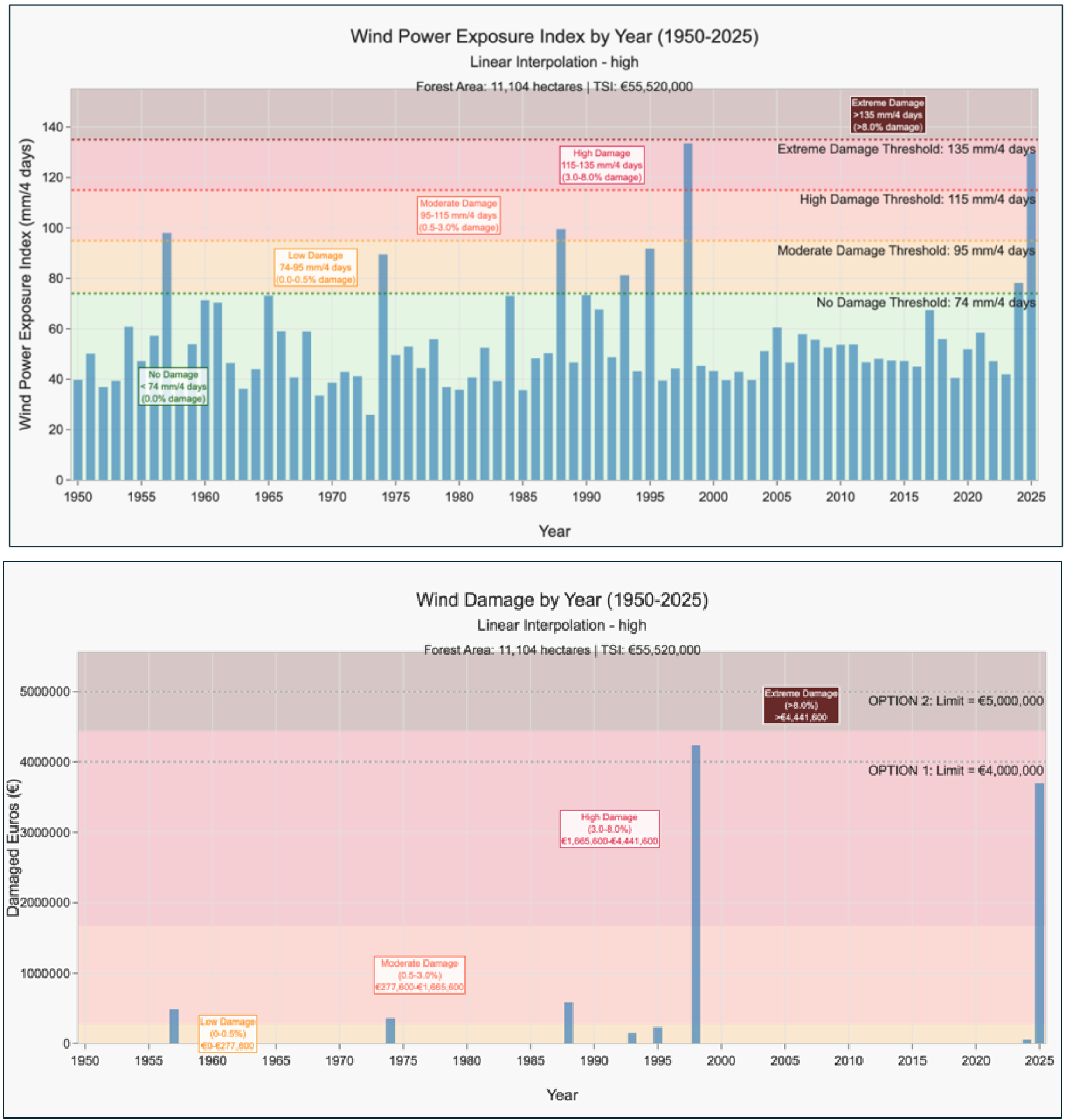
- The index was then combined with the vulnerability curve to get payouts (Figure 7), where the damage is computed directly from WPEI, and vulnerability curves were computed from vulnerability maps previously developed.



Source: AXA Climate

Figure 7: Illustration of the Vulnerability Curve

- The yearly historical values of the WPEI and the as-if historical damage were then modelled (Figure 8), which can be used as a risk management tool to help the client make the best decision around limits given historical as-if payments.



Source: AXA Climate

Figure 8: Wind Power Exposure Index (above) and Wind Damage (below) by Year

- Based on the as-if reconstructed historical losses and index values, a distribution is fitted with some constraints applied to fit a known return period of severe windstorms (Figure 9). The price is then computed based on a sampling of 10,000 years.

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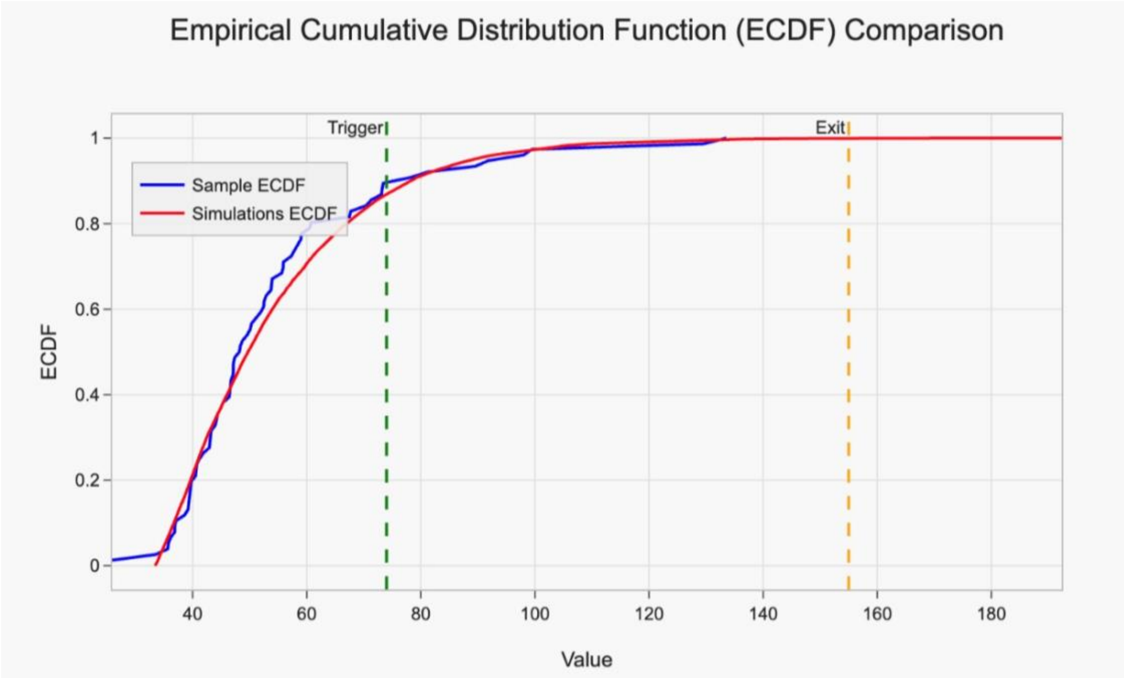
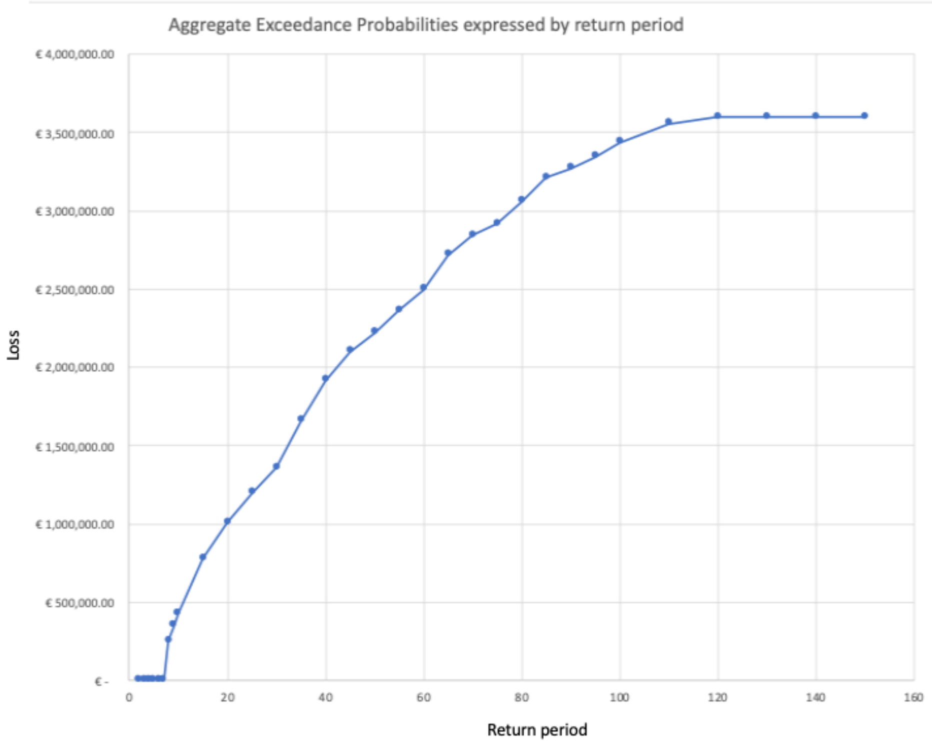


Source: AXA Climate

Figure 9: Empirical Cumulative Distribution Function Comparison

- Pricing comparisons between parametric product and traditional covers are often confusing as they are not necessarily targeting the same layer of risk and because parametric pricing is considerably more sensitive. Still, to give an anchor, Figure 10 proposes here a product with a payout trigger every 8 years and a full loss every 100 years, as expressed by the return period.



Source: AXA Climate

Figure 10: Aggregate Exceedance Probabilities expressed by return period

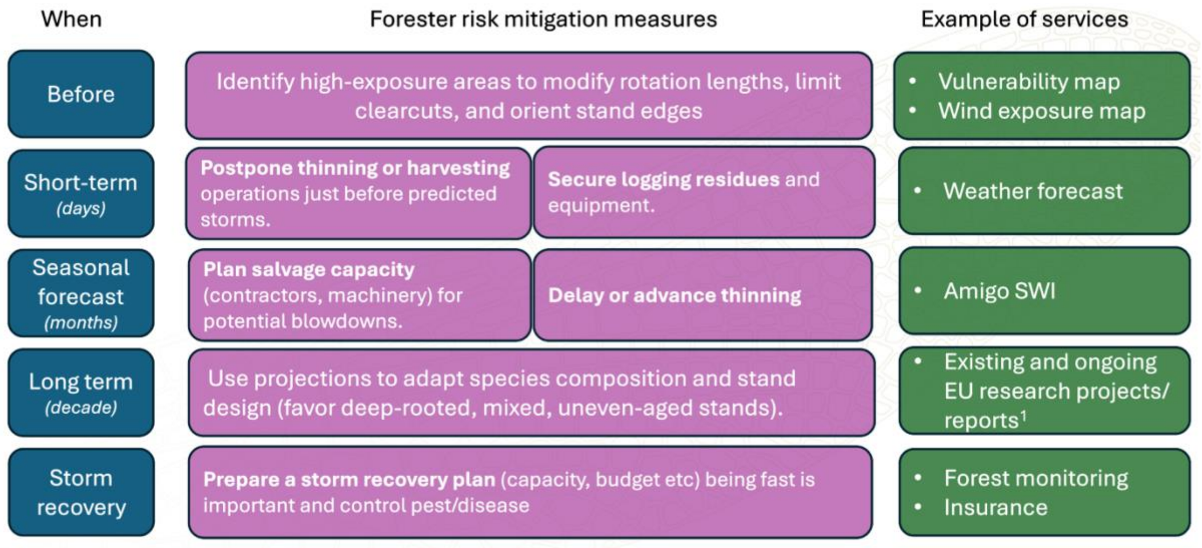
- This process led to a RoL of 7%. To compare it to an indemnity product, this can also be re-written as having a cost of 5.4€/ha/year for an insured value of 1,000€/ha. In the illustrative example, the value per hectare of the insurable interest (storm cleaning, planting minus the salvage value) was 5,000€/ha, leading to a 27€/ha for the premium. In other words, the insurance cost represents 0.5% of the asset value for the forester.
- The price of this cover (5€/1000€) seems a bit above the mean Willingness-To-Pay (WTP) evaluated for standing timber insurance by Yiling D. et al. (2015) at 3€/1000€. Nonetheless, as the region studied here is extremely exposed to high winds and the vulnerability is high, it is reasonable for it to be at the higher end of the spectrum. Secondly, as the study mentions, present covers are largely more expensive, noting most of the respondents were paying a rate between 8€ to 10€ per 1,000€ of timber value.
- In conclusion, the product is price competitive while benefiting from fast payouts and valuable insights for risk management due to the parametric insurance structure.
- The model can also be updated later to add modules such as soil moisture/ice melt characteristics into the existing index.

2.2.4. Loop 3: (October 2025-February 2026)

Loop 3 focused on consolidating the modelling and pricing developments achieved in Loops 1 and 2, validating stakeholder relevance, strengthening climate service components, and defining a clear pathway for replication beyond the pilot region.

Climate services

Loop 3 focused on strengthening the climate-service dimension of the product. The WPEI index, built on Copernicus ERA5 land data, already provides a transparent and replicable climate input. During validation discussions, additional climate services examples were explored, outlined in Figure 11, disaggregated based on the timeline of need.



Source: AXA Climate

1. Gardiner, et al., (2010 and 2013); Spinoni, et al., 2020

Figure 11: Forest climate services based on time-span

Stakeholder Validation and Webinar

To test the broader relevance of the windstorm insurance framework beyond the pilot context, a webinar was organized on 9th February, 2026, in collaboration with the EU Precilience project, with a particular focus on boreal forest regions. The objective was two-fold: (i) to present the modelling framework, vulnerability mapping, and pricing estimates developed under this pilot, and (ii) to gather structured feedback from forestry stakeholders, insurers, and climate-service providers in the region.

During the webinar, a real-time questionnaire was conducted (via Mentimeter) to collect insights on:

- Perceived barriers to forest insurance uptake
- Willingness-to-pay levels and acceptable premium ranges
- Priority risks and preferred coverage structures
- Interest in and expectations from climate services

The results confirmed and refined several patterns observed during the pilot:

- A key barrier to wider forest insurance uptake is that existing products are often not sufficiently adapted to forest owners' operational realities. Participants highlighted that some insurance products compensate for post-event cleaning costs but do not adequately cover clearing and replanting activities, which are essential for long-term forest recovery and resilience.

- Regarding WTP, the Mentimeter results indicated a general acceptable range of €5-10 per hectare, broadly consistent with earlier estimates and findings (which was at ~€5 per hectare). Participants also indicated that they largely do not see a trade-off between the uptake of insurance versus the deployment of adaptation measures due to budget constraints. Primary mitigation or adaptation measures implemented involved the diversification of species, uneven age, etc.

- Existing climate services being used included short-term meteorological forecasts, seasonal climate forecasts, and forest monitoring services. Ideal improvements in existing services included better forecast horizons with accuracy, better frequency of data, and better estimates for wind speed.

Following the webinar, a dedication work session was held with AXA Climate, AXA Germany, Amigo, and Tyrsky to validate the technical insights, review stakeholder feedback, and identify operational next steps. This session included an overview and recap of the project, and an in-depth discussion on the barriers highlighted during the webinar.

The misalignment between coverage structures and resilient forest management needs was identified as a gap; if insurance products cannot be tailored to client needs, it weakens their credibility and reduces the perceived value of associated climate services. It was also stressed that forestry risks are interlinked: windthrow, drought stress, bark beetle infestation, and other disturbances often reinforce one another. While forest managers must adopt a systemic perspective, insurers typically cover risks individually, which can limit the comprehensiveness of coverage and complicate product design.

Discussions on WTP revealed important contextual nuance. In Germany, even high-risk areas may currently be insured at levels substantially lower than those projected under the pilot modelling assumptions. This discrepancy was partly explained by Germany’s comparatively lower wind risk (approximately three times lower than Scotland), which reduces actuarial pressure and, in practice, may make parametric structures less economically compelling in low-risk contexts. The discussion also addressed the perceived lack of trade-offs between investing in adaptation versus purchasing insurance. In the German context, stakeholders noted that this is not necessarily a zero-sum trade off. Many adaptation measures (e.g. species diversification, structural heterogeneity, uneven age stands) provide direct ecological and economic benefits beyond risk reduction. When combined with potential premium discounts, this reduces the likelihood of a behavioral trade-off and instead supports a complementary relationship between adaptation and insurance.

With respect to climate services, participants emphasized the importance of improving technical precision and usability. A critical distinction was highlighted between average wind speeds and gust speeds, the latter being significantly more relevant for windthrow risk. Additionally, stakeholders stressed that vulnerability varies substantially by stand characteristics and species composition, information that is often difficult to access at sufficient spatial resolution. Ideal improvements to climate services therefore include:

• Better differentiation between wind speed metrics (mean vs gust)
• Improved forecast horizons with higher reliability
• More frequent and higher-resolution data
• Enhanced integration of stand-level characteristics into risk assessments

Replicability roadmap

In collaboration with LGI, a replicability roadmap was developed, which will be published independently as D4.7, focusing on the replicability for all pilots. The replication focus is on the transfer and adaptation of wind risk models to support insurance product design in other forested areas across Europe. Overall, the primary goal is to continue the testing and validation of wind models in additional European regions. Complementarily, this deliverable documents the methodological processes and requirements, calibration steps, and data needs for replication in different ecological and regulatory contexts. Below is a short summary of the key actions outlined in the replicability roadmap:

Priority actions for post-project replication:

Vulnerability index:

- Deploy the index in regions with comparable forest and storm characteristics.
- Ensure outputs integrate local forest characteristics (species composition, stand structure), soil conditions, and topography.
- Maintain scalability while allowing improvement through regional ground-truth calibration.
- The model has already been calibrated in regions across Germany, Ireland, Scotland, Denmark, and France; replication beyond these areas requires structured recalibration. For example, in the Boreal region, modelling needs to account for the occurrence of deep soil frost which reduces vulnerability to windfall damages.

Wind Power Exposure Index (WPEI)

- No structural development is required, as the WPEI integrates wind intensity and wind direction using open-source ERA5-Land data, which is globally available.
- The historical hazard component of the WPEI can also be deployed independently as a climate service, enabling forest owners to assess historical wind exposure and calibrate their own risk appetite.

Damage curves and insurance integration

- Insurance companies integrating the framework should combine the WPEI and Vulnerability Index with their internal pricing strategies.
- Particular attention should be paid to aligning model outputs with underwriting thresholds and deductible structures.

Key conditions and dependencies:

- Data Availability: Access to harmonized forest inventory and stand-level data.
- Availability of reliable wind and storm records.
- Insurer Engagement: Willingness of insurance partners to integrate model outputs into underwriting practice.
- Regional calibration as replication without local calibration significantly reduces accuracy. Ground-truth validation using historical storm events is strongly recommended, which would also be needed before the contractualization of any product.

Replication horizon: Short to medium term, given that required climate datasets (e.g. Copernicus ERA5) are available at a European scale and the modelling architecture has demonstrated transferability.

Overall, replication is technically feasible at a European scale due to the availability of ERA5 data and transferable modelling architecture. However, robustness depends strongly on careful regional recalibration and historical back-testing before commercial deployment.

2.3 Closing remarks

This pilot confirmed that the windthrow insurance prototype developed under PIISA is technically robust, economically sound, and structurally replicable. While purely parametric structures may not be optimal for all forest types or risk layers, the combined modelling framework – integrating hazard characteristics, stand-level vulnerability, and actuarial simulations – provides a credible foundation for climate-sensitive forestry insurance for windstorms.

The pilot demonstrates that high-resolution climate and forest data can meaningfully reduce basis risk; vulnerability-based differentiation in forest management reduces risk against windstorms, thereby improving pricing outputs; parametric structures and triggers enhance transparency for clients; and that climate services and insurance can be mutually reinforcing.

Together, these elements contribute to a scalable approach for reducing the forest protection gap in Europe and strengthening the financial resilience of forest ecosystems under increasing climate stress.

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3. Pilot 2: Wildfire risks in Portugal

3.1. Motivations and objectives of the pilot

Portugal is increasingly exposed to severe and recurrent wildfires, driven by rising temperatures, prolonged droughts, and changing land-use patterns. One of Europe's most fire-prone regions, Portugal has experienced severe damages and casualties due to wildfires (Galizia, et al., 2021). Recent fire seasons (such as the extreme fires of 2017) have shown that wildfire impacts are no longer episodic but structural, leading to loss of lives, significant economic losses, repeated ecological damage, and growing pressure on public compensation mechanisms. Severe impacts have raised wildfire management to a high priority in disaster risk reduction and climate change adaptation policies in Portugal. Concurrently, this adverse evolution significantly challenges the long-term insurability of forests and rural assets. At the same time, Portugal's forestry sector is crucial to the economy, covering about 35% of Portugal's land area, and contributing approximately 2.5% to the country's GDP (ClimateChangePost, n.d.).

Despite the high level of risk, insurance uptake for wildfire remains limited, with a deep-dive on the Portuguese forestry sector and insurance market provided in PIISA deliverable 1.4 (Lameh, et al., 2024). A large protection gap persists, linked to low risk awareness and affordability constraints. When looking at the estimated share of wildfire losses insured across 1990-2019, Portugal was only insured for 10% of its losses in that period (OECD, 2021). At the same time, Portugal, through the Agency for Integrated Rural Fire Management (AGIF), is developing a wide range of forest management and fuel-reduction strategies, although these adaptation efforts are rarely reflected in insurance pricing or coverage conditions. Through their National Adaptation Plan (NAP), Portugal has laid out a detailed plan with goals to achieve the reduction of cumulative burned areas, the percentage of large fires, and the reduction of losses of lives in rural areas. This is aimed to be done primarily through the development of a primary and secondary network of fuel management strips, or fire breaks, which are the main adaptation measures used in this pilot to assess potential risk and insurance premium reductions, thereby making this pilot a crucial tool toward validating Portugal's policy objectives.

In parallel, there is growing interest in carbon-related insurance mechanisms, which remain at a very early stage of development. Forest wildfires represent a major source of uncertainty for carbon sequestration, as extreme fire events can rapidly reverse decades of accumulated carbon stocks and undermine the credibility of forest-based carbon projects. By reducing fire frequency and intensity, effective wildfire risk mitigation can therefore help stabilize long-term carbon storage, lower reversal risks, and increase confidence in forest carbon assets. This creates a potential linkage between wildfire risk reduction, parametric insurance, and emerging carbon insurance or risk-buffer mechanisms, where improved fire resilience could support the durability and insurability of carbon sequestration outcomes.

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The objective of the Portugal pilot is to integrate adaptation measures into parametric wildfire insurance design, allowing risk reduction efforts to be explicitly modelled and priced. By linking hazard, exposure, vulnerability, and adaptation actions within a parametric insurance framework, this pilot aims to assess whether adaptation can generate economies of scale (cost savings gained by an increased level of participation), premium reductions, and improved affordability, thereby supporting both climate resilience and sustainable insurance solutions.

3.2. Development cycles and methods

In terms of overall structure, this pilot was also constructed and implemented by following loop-based iterative design (also called development cycles) and development feedback with constant stakeholder input and engagement to ensure robust and relevant outputs. Methods combined climate science, forest risk modelling, actuarial techniques, and stakeholder engagement. There was also consistent communication with work package 2 to ensure alignment and benefit from climate services and index development.

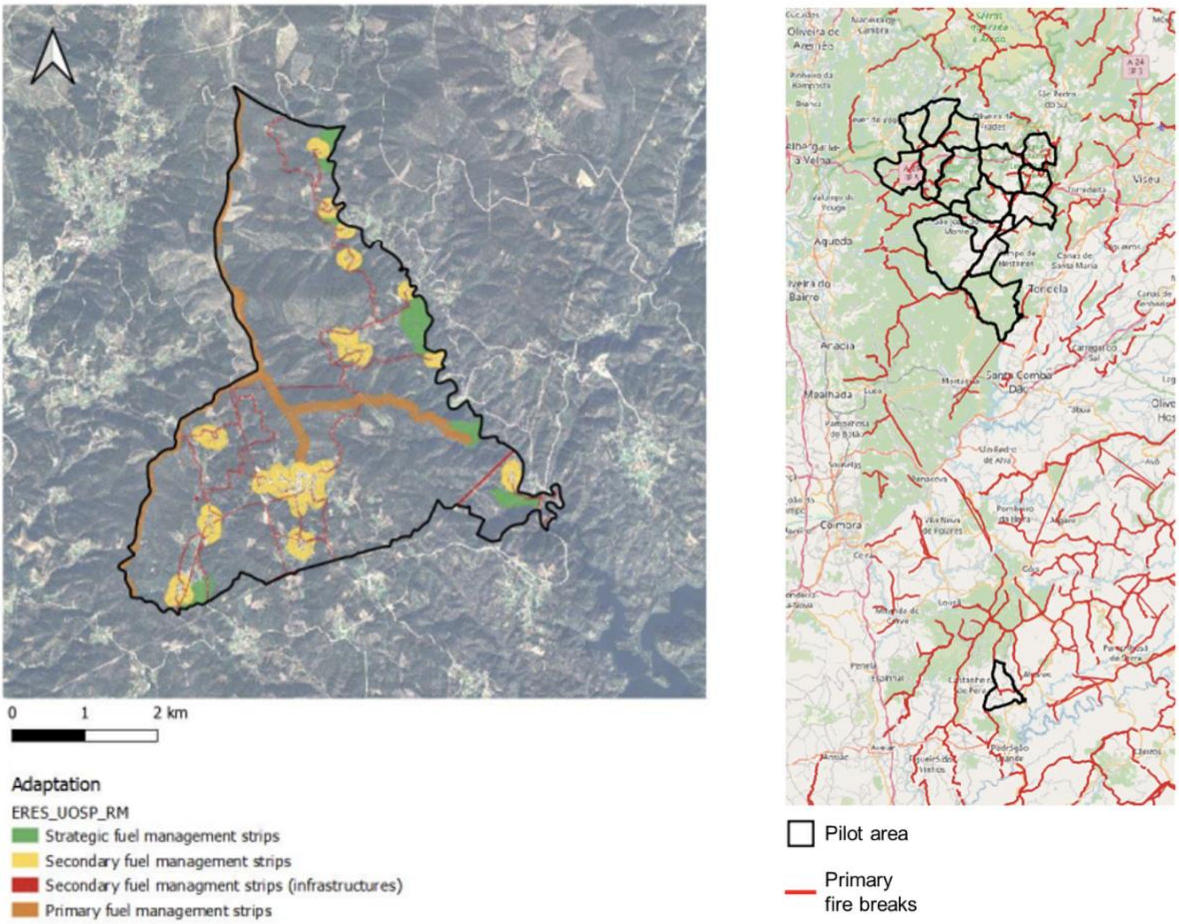
3.2.1. Summary of work conducted and previously published in September 2024 (Loop 1: November 2023-May 2024, and beginning of Loop 2: May 2024-August 2024)

Loop 1 of this project focused on assessing high-risk wildfire areas in Portugal, choosing the study area in Central Portugal, and gathering key datasets to map current wildfire risks. It included a systemic review and assessment of AGIF's planned adaptation and mitigation plans based on Portugal's NAP, which were used to develop various wildfire mitigation scenarios. These scenarios then inform the design of innovative insurance models in Loop 2, which incorporates wildfire risks and adaptation measures in the pricing model.

This work is documented in previously published PIISA Deliverable 3.10: Preliminary Design of the New Insurance Instrument (Kochar, Galizia, et al., 2024). The initial phase of the Portugal pilot defined its background, motivation, and objectives, with a geographic focus on the Caramulo and Ribeira de Mega region in Central Portugal. This area was selected due to its history of significant wildfire losses, diverse exposure patterns, and the presence of well-developed adaptation plans. A detailed review of national and regional adaptation strategies was undertaken to identify measures that could be meaningfully integrated into insurance design. Particular attention was given to two key adaptation strategies:

1. The primary network of fuel management strips (fire breaks aimed at intercepting the fire spread and creating favorable conditions to stop fires), and
2. The secondary network of fuel management strips (to stop the fire spread passively, protecting routes, infrastructure social facilities, and built-up areas), as shown in Figure 12 for the Ribeira da Mega area, including different fuel management strip types to decrease wildfire risk in the study region.

This phase also involved extensive data collection and harmonization using open-source datasets, including significant processing efforts to prepare consistent model inputs. A wildfire hazard model was then developed and calibrated, linking fire occurrence and intensity to exposure and vulnerability patterns. Early calibration efforts focused on reproducing large historical fires as well as overall fire size distributions and burned areas. Together, these activities established the methodological foundation of the pilot, demonstrated technical feasibility, and clarified priority areas for further refinement. Subsequent development cycles build on this groundwork to test, improve, and operationalize adaptation-integrated wildfire insurance solutions.



Source: AGIF (left), and ICNF (right)

Figure 12: Overview of the adaptation measures implemented in Ribeira de Mega (left), and across the study area (right)

3.2.2. Remainder of Loop 2: Building the insurance framework (September 2024- February 2026)

The model calibration process was continued, which included reproducing extreme fire events, and reproducing fire regimes and fire size distributions. For reproducing extreme events, the following methodology was employed

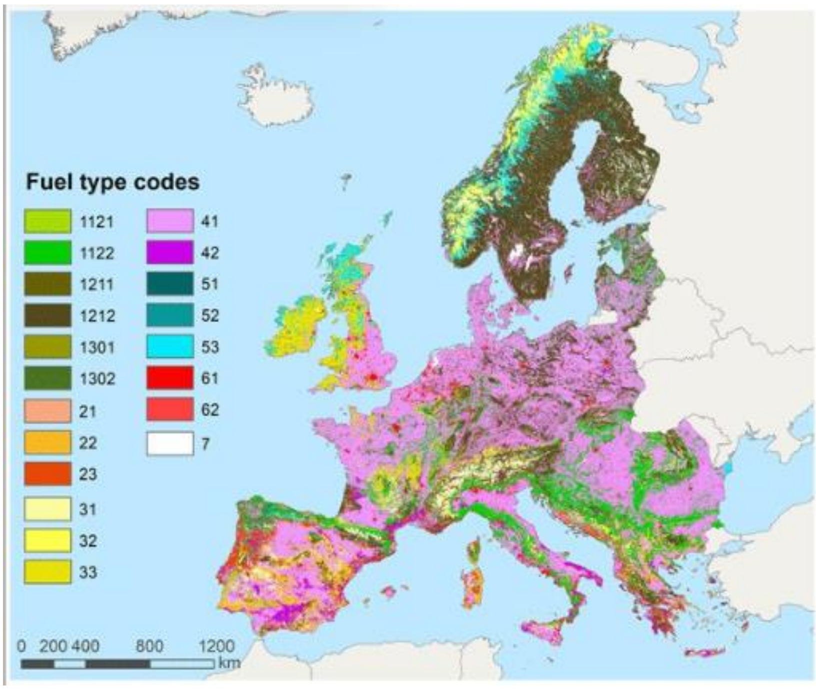
- Selection of 4 large fire events observed in the study area
- Simulation of single fire spread considering extreme fire weather conditions
- Testing of two different fuel classifications: continental (EU) and regional (Portugal)
- Testing different fire spread models

- Comparison of fire footprints (% of overlap) and area burned

Wildfire hazard modelling

Two complementary wildfire spread models were utilized and calibrated in parallel in order to account for modeling uncertainty.

1.**Minimum Travel Time (MTT)** Fire Spread Model: Led by AXA Climate, this model is based on constant environmental conditions based on Rothermel's 1972 surface fire spread model (Rothermal, 1972). It incorporates input variables such as fire weather (temperature, relative humidity, windspeed, and direction), and United States Department of Agriculture (USDA) fuel codes.

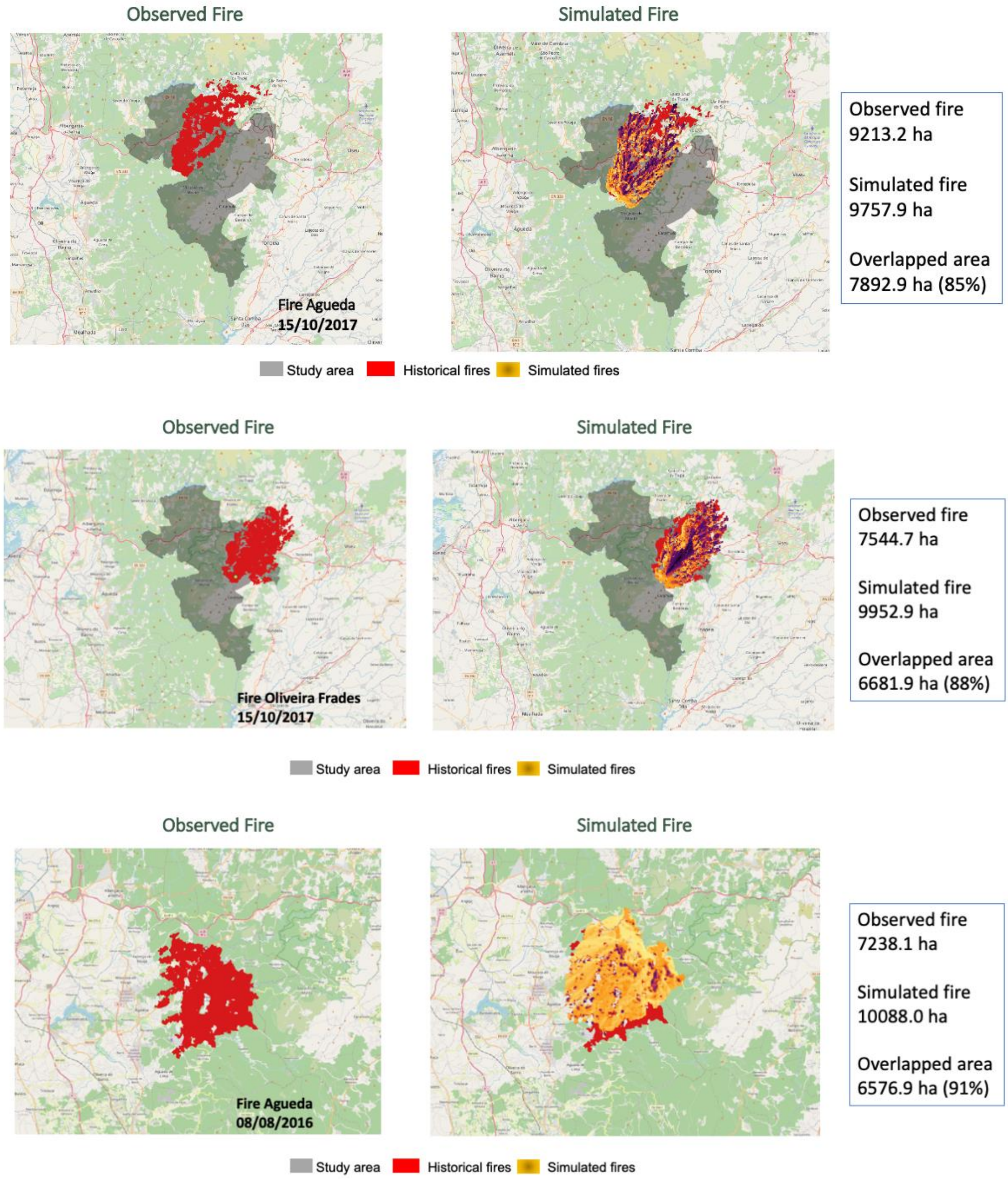


Source: Aragoneses et al., 2023

Figure 13: Overview of spatial distribution of the various fuel type codes

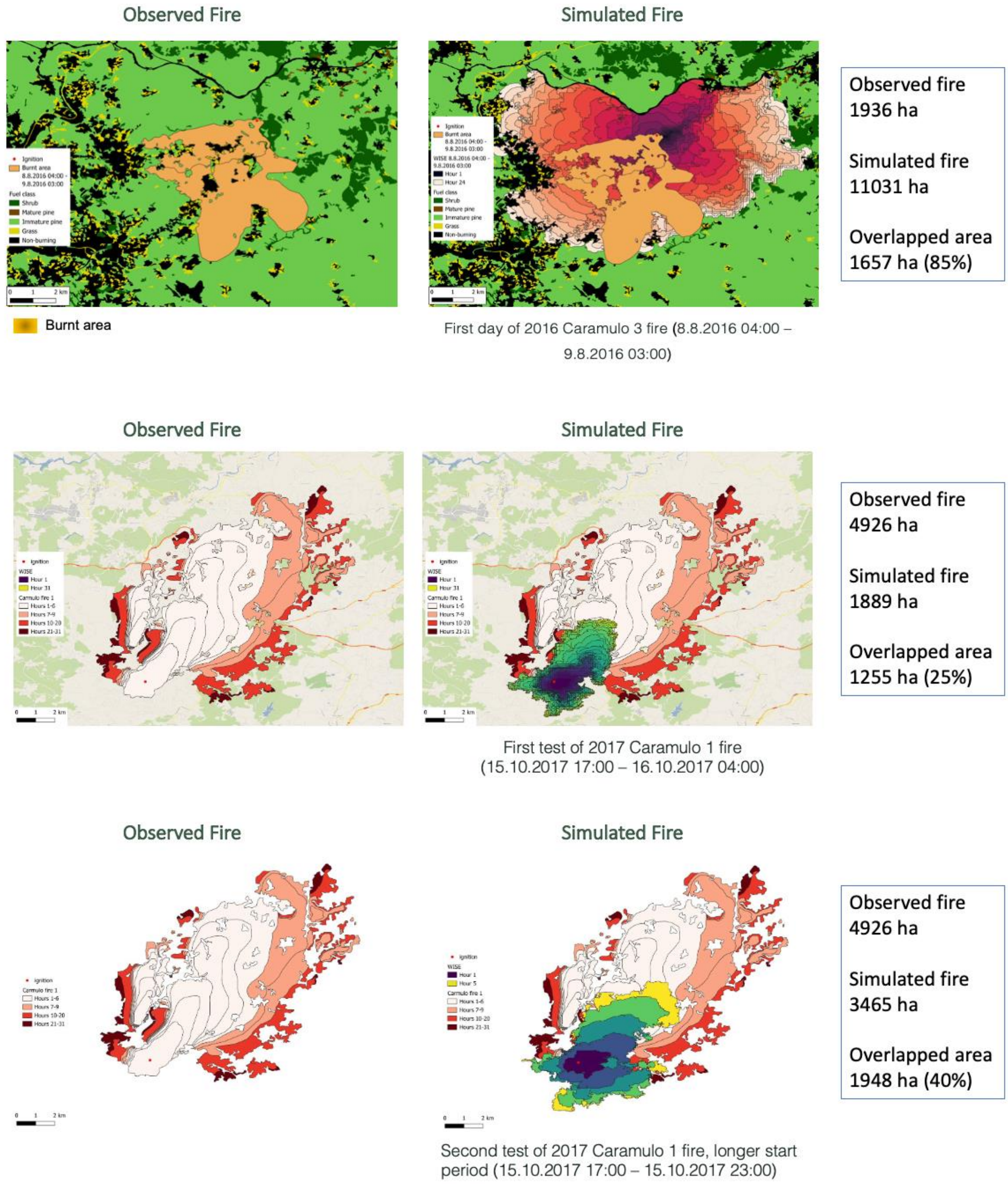
2.**Wildfire Intelligence and Simulation Engine (WISE)** Fire Spread Model: Led by FMI, this model is a dynamic open-source wildfire propagation modelling system based on the Canadian Fire Weather Index (FWI) and Fire Behavior Prediction (FBP) systems. It incorporates input variables such as hourly weather (temperature, relative humidity, wind speed and direction, and precipitation), FBP fuel type, elevation, and additional information regarding fuels, physical barriers, etc. The model runs in hourly time steps, generating fire propagation points along the current fire perimeter, calculating propagation from each of them based on windspeed, elevation, etc., and finally creates the new perimeter. Fuel type classification is based on the FBP Canadian system, showing major differences in level of detail in fuel types when compared with the USDA system used in MTT model, with grouping needs necessary for some of the fuel types, with the differences broken down in Appendix 2.

Once these models were set up, they were tested by analyzing their ability to reproduce extreme historical fires, with initial replications shown in Figures 14 and 15 for MTT and WISE models respectively.



Source: AXA Climate

Figure 14: MTT fire simulation reproductions for Fire Agueda (2017, top), Fire Oliveira Frades (2017, middle), and Fire Agueda (2016, bottom).



Source: FMI

Figure 15: WISE fire simulation reproductions for Caramulo 2016 and 2017 fires

Key takeaways from the first fire analysis include:

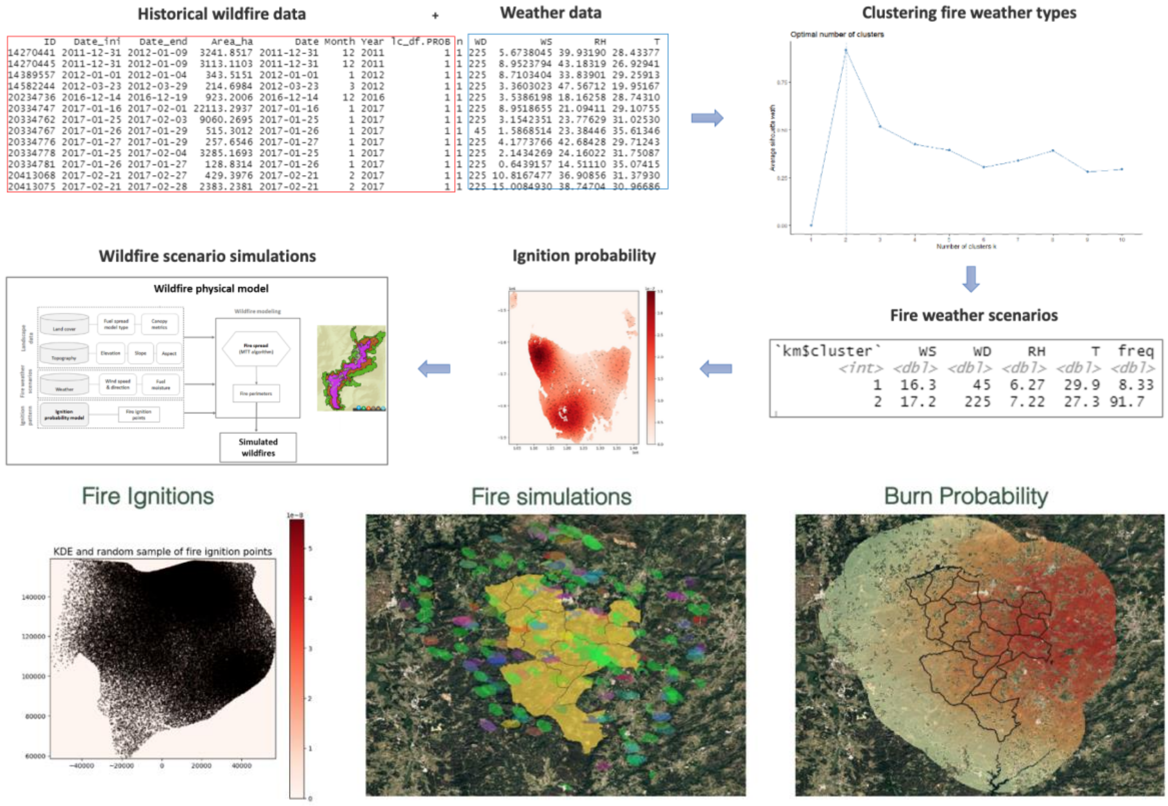
- Using standard USDA fuel models calibrated for Europe with Portuguese land cover presented consistent results
- Fire models showed sensitivity to climate variables in the single event analysis

- Fire models can reproduce fire spread patterns with varying levels of prediction accuracy. For instance, MTT simulations showed very promising results, with 85-92% overlapped areas between historical and simulated fires across different historical fires, with WISE model accuracy ranging from 25-85%.
- Preliminary results showed overestimation as well as underestimation of fires in WISE simulations. Reasons include the lack of firefighting measures in simulations leading to overestimation, and fuel type estimate comparisons and the short weather dataset, leading to smaller fires; this can be adjusted by modifying the burning period in subsequent simulations. An improvement was made in refining the WISE workflow (simulation time x resolution) and expected progress in the calibration phase
- Subsequent simulations included the refinement of fuel type classifications, sensitivity analyses, and testing additional fires. Standard fuel models instead of custom Portuguese fuel models were retained following AGIF's recommendation, as it would better facilitate the inclusion of adaptation measures in the model simulations.

Fire Model Calibration

Following the fire model sensitivity analysis for extreme events, the fire models were calibrated to reproduce the historical patterns (i.e. fire regime), by building fire weather scenarios, simulating thousands of fires considering observed fire weather conditions, comparing simulation and observed fire size distributions, comparing simulated and observed annual burned areas, comparing spatial patterns of annual burn probability, and building the wildfire catalogues (simulated fire footprints for a thousand years). Figure 16 outlines this process.

Key challenges in the process were to account for the differences in the models, given the MTT model simulations assume static weather scenarios and WISE model simulations focus on dynamic weather conditions, different fuel model systems, simulation time and computing resources, and input data uncertainty.



Source: AXA Climate

Figure 16:Framework for wildfire simulation using fire spread models.

Initial calibration results for the MTT model are provided in Figure 17, showcasing the post-processing fire simulations (across 1000 years), annual burn probabilities, and fire risk maps (which can be used for computing annual expected losses). In terms of ignition data sources, MCD64A1 Version 6.1 Global Burned Area data product from MODIS satellite was used since it provides daily, global gridded 500m information on burned areas. MCD64A1 was found to be good to be used for medium to large fires, but not ideal for small fires due to its coarse spatial resolution.

To calibrate the fire spread models, a vast collection of plausible simulated fires was generated across a wide range of observed climate conditions in the study region. SCENFIRE, a Post-Processing Scenario-Based algorithm for the integration of Wildfire simulations, was used to calibrate the model to reproduce historical fire size distributions in the simulations. The algorithm assembles individual fire perimeters based on their specific probabilities of occurrence, determined by (i) the likelihood of ignition, and (ii) the probability of particular fire-weather scenarios, including wind speed and direction. This method offers several significant advantages. First, it eliminates the need for fine-tuning simulation parameters by creating an extensive pool of scenarios, which can be automated using scripting tools such as FConstMTT batch processing. Second, it allows for easy adaptation to various fire size distributions without necessitating recalibration of the simulation process.

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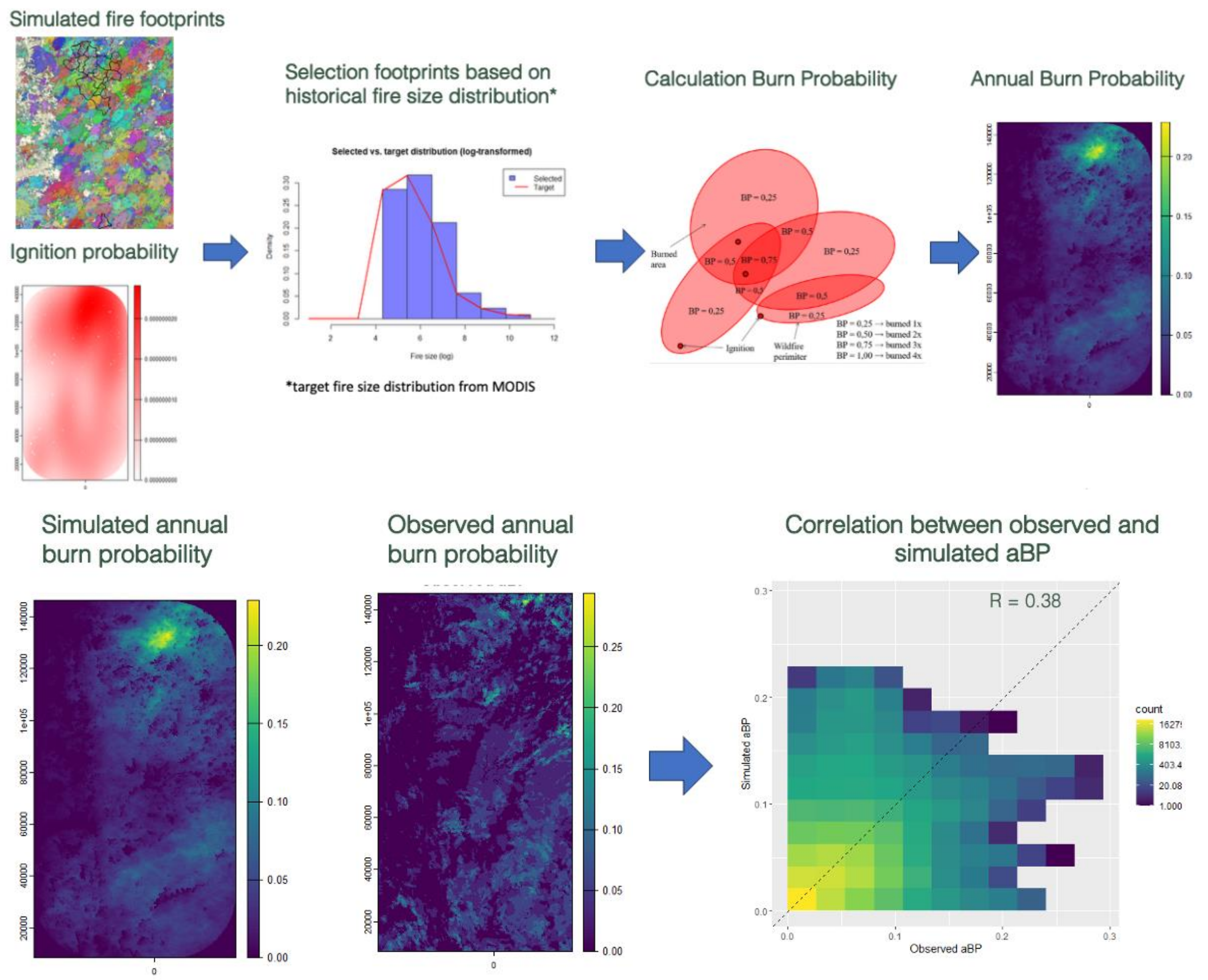
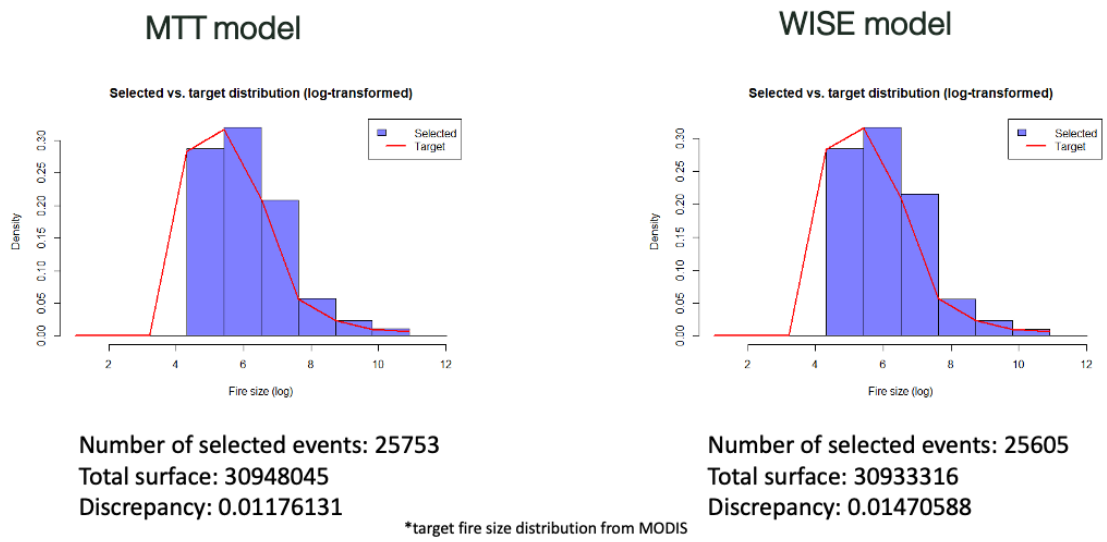


Source: AXA Climate

Figure 17: Overview of the framework used to calibrate the fire spread models.

Figure 18 showcases the results for the fire model calibration for both fire spread models in comparison with the MODIS observations, showing both the fitted fire size distributions and discrepancies.

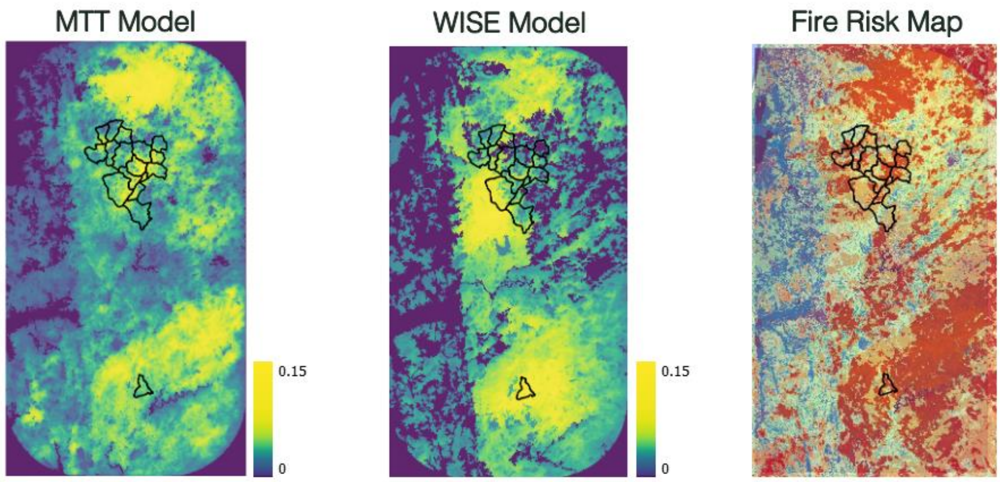


Source: AXA Climate

Figure 18: Results of the fire model calibration for the MTT and WISE models, showing the fitted fire size distribution and discrepancy in comparison with the MODIS observations

Results of the fire model overall show a good alignment with historical fires and official risk maps of Portugal, though there are some limitations around the ignition modelling, as ignition probability is currently simplified by kernel density distribution.

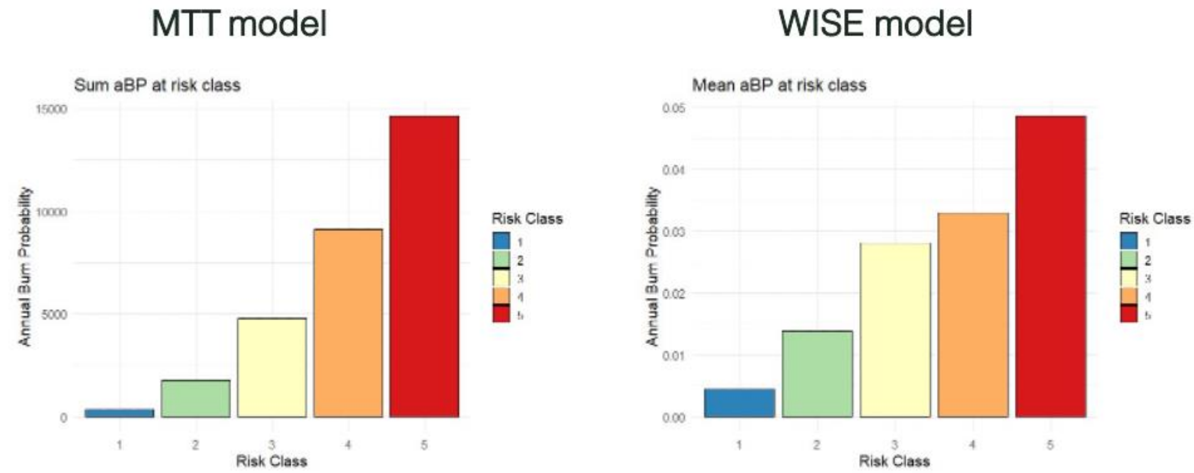
Figure 19 shows the historical annual burn probability maps developed using the MTT and WISE models, with AGIF's fire map provided alongside for the purpose of comparison.



Source: AXA Climate, FMI, and AGIF

Figure 19: Development process of the historical annual burn probability and fire risk maps

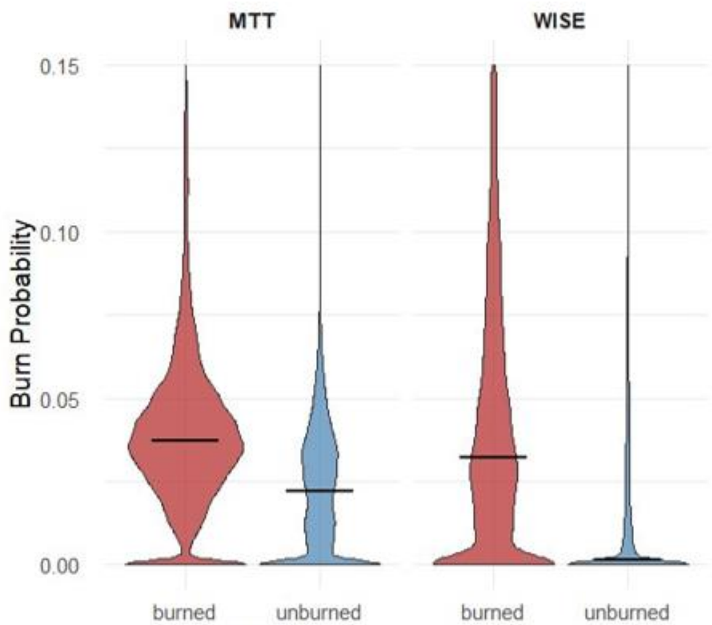
Discussions with AGIF on the official fire risk "structural" map, created by the Institute for Nature Conservation and Forests (ICNF), provided insights that it is updated every year and used to deliver construction permits, and therefore very relevant for concrete impacts on the built environment. MTT and WISE models were compared against the structural risk map to evaluate the consistency of their outputs. Mean annual burn probability was calculated for each risk class (1 – low to 5 – very high). As expected, burn probability increased with risk class for both models. MTT produced higher burn probabilities in the lower risk classes compared to WISE, suggesting a more conservative approach, yet both models converged in the highest risk classes which are the most critical, as they account for the majority of wildfire damage (Figure 20).



Source: AXA Climate and FMI

Figure 20: Mean annual burn probability of both models for each risk class of the structural fire risk map

MTT and WISE were further evaluated against historical wildfire data from MODIS. Using a similar approach, mean annual burn probability was extracted separately for burned and unburned pixels to assess whether the models can effectively differentiate areas with a history of fire damage from those without. Results indicate that both models successfully reproduce historically burned areas, assigning higher burn probabilities to pixels with recorded fire activity than to those without (Figure 21). MTT yields more conservative estimates, attributing some probability to unburned pixels as well which may be appropriate, since the absence of historical fire does not necessarily imply low future risk. Regardless, both models show a clear and consistent distinction between burned and unburned classes.

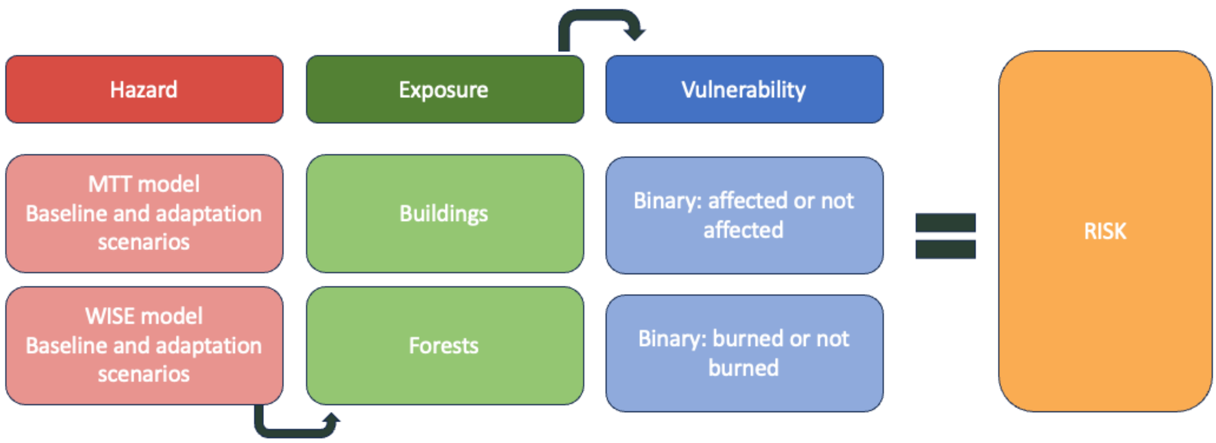


Source: AXA Climate and FMI

Figure 21: Mean annual burn probability of both models, calculated across pixels with recorded fire activity in the MODIS dataset over the 2001-2024 period. The horizontal line represents the median within each respective class

Overall, fire models originally present good agreement with the observed fire data, but differ in some areas due to different methods used for fire simulations.

The risk assessment framework as outlined in Figure 22 provides a structured visual overview of how insurance-relevant fire risk is calculated as the interaction between hazard, exposure, and vulnerability. The hazard component is modelled through two parallel scenarios across the two models: a baseline scenario representing current conditions, and an adaptation scenario reflecting the implementation of risk-reduction measures. Exposure is treated separately for forests and buildings, allowing differentiated assessment of ecological and asset-based values. Vulnerability is captured through binary impact states – affected versus not affected, and burned versus not burned – which determines the extent of loss once hazard intersects with exposure. The combination of these three components – hazard x exposure x vulnerability – produces an integrated estimate of expected risk for insurance design and pricing purposes.



Source: AXA Climate

Figure 22: Visual representation of the calculation of fire risk

<u>Wildfire adaptation scenario modelling</u>

As a reminder, there are two main wildfire adaptation scenarios that will be explored within the context of the insurance framework, as taken from Portugal's National Adaptation Plan (NAP). A primary network of fuel management strips, which directly aim to intercept the fire spread and create favorable conditions to stop fires, and a secondary network of fuel management strips, which serve to stop the fire spread by passively protecting routes, infrastructure, social facilities, and built-up areas. Both these adaptation measures were modelled by setting the fire break strips as non-fuel areas. Primary fire breaks are designed to interrupt large wildfire spreads and support firefighting operations, and are implemented at the national scale with a width of 100 m. Secondary fire breaks aim to protect vulnerable structures and are located in wildland-urban interface areas, with widths ranging from 50 to 100 m depending on the number of structures exposed. However, fire or fuel breaks require regular maintenance, as vegetation regrowth can reduce their effectiveness in limiting wildfire spread and mitigating the impacts. To account for this, an

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intermediate adaptation scenario was also included, in which partial fuel removal was assumed to represent unmaintained or degraded firebreak conditions. All the simulated scenarios are presented in Table 3.

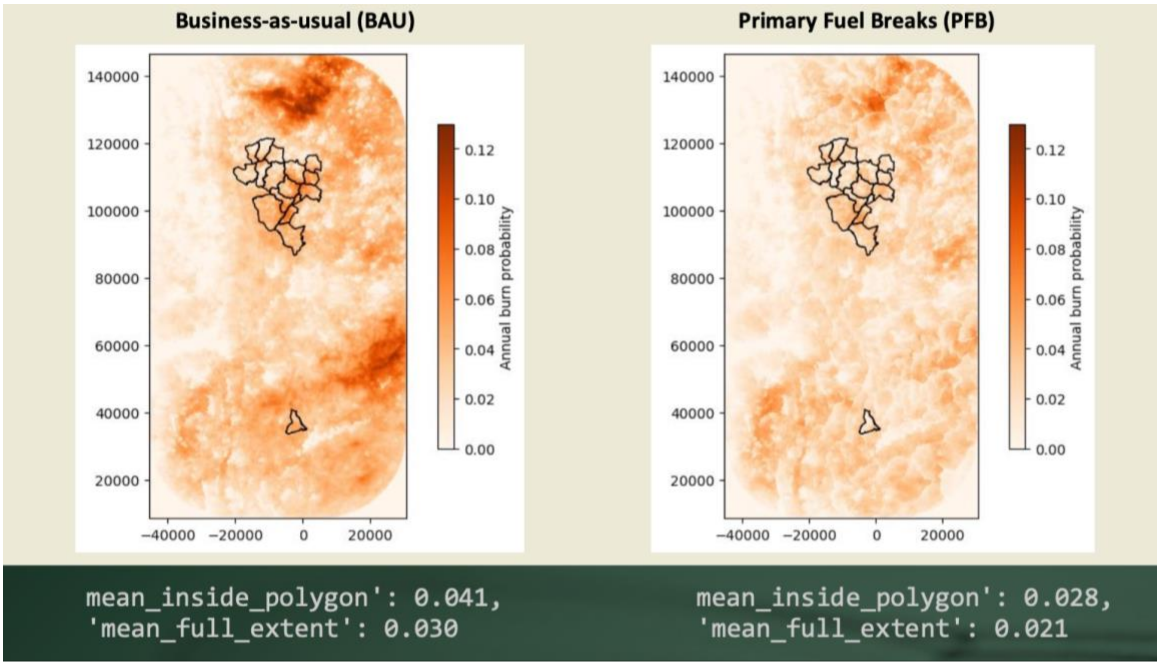
The modelling adaptation scenarios chosen are outlined as follows:

Scenario	Acronym	Description
Business as usual	BAU	Current landscape without fuel breaks
Primary fuel breaks	PFB	Primary Fuel Breaks with complete removal of the vegetation
Primary and secondary fuel breaks	PSFB	Primary and Secondary Fuel Breaks with complete removal of the vegetation
Primary fuel breaks – partial removal	PFB-PR*	Primary Fuel Breaks with partial removal of the vegetation
Primary and secondary fuel breaks – partial removal	PSFB-PR*	Primary and Secondary Fuel Breaks with partial removal of the vegetation

Table 3: Overview of adaptation scenarios

*complementary scenarios included for sensitive analysis on the maintenance of the fuel breaks, not included in the pricing.

Annual burn probability results from the MTT and WISE models are provided in Figures 23 and 24 respectively, showing a clear reduction in burn probability, with varying levels of reduction depending on the area risk levels, adaptation measured, and wildfire models.



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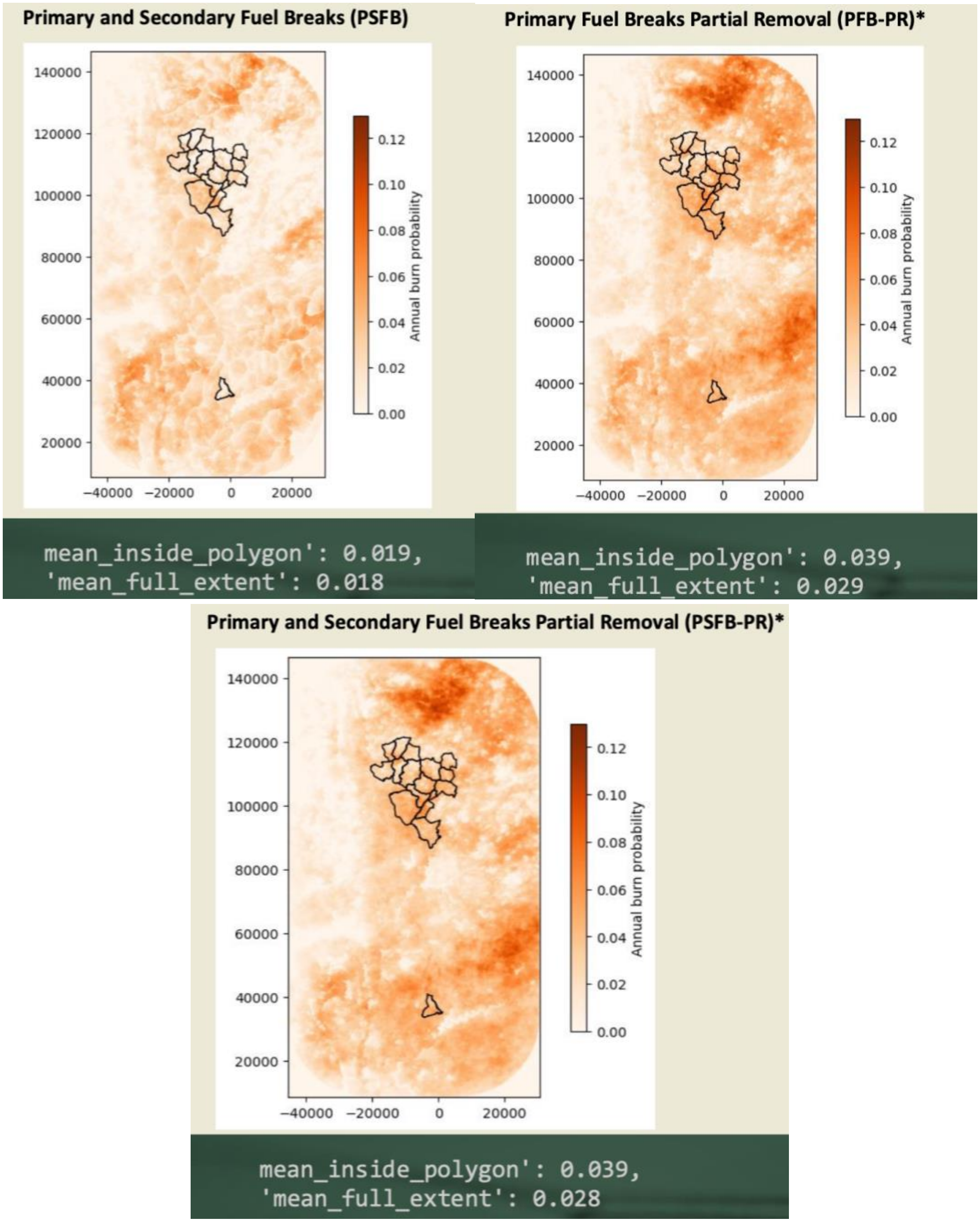

Source: AXA Climate

Figure 23: Annual burn probability results for the MTT model

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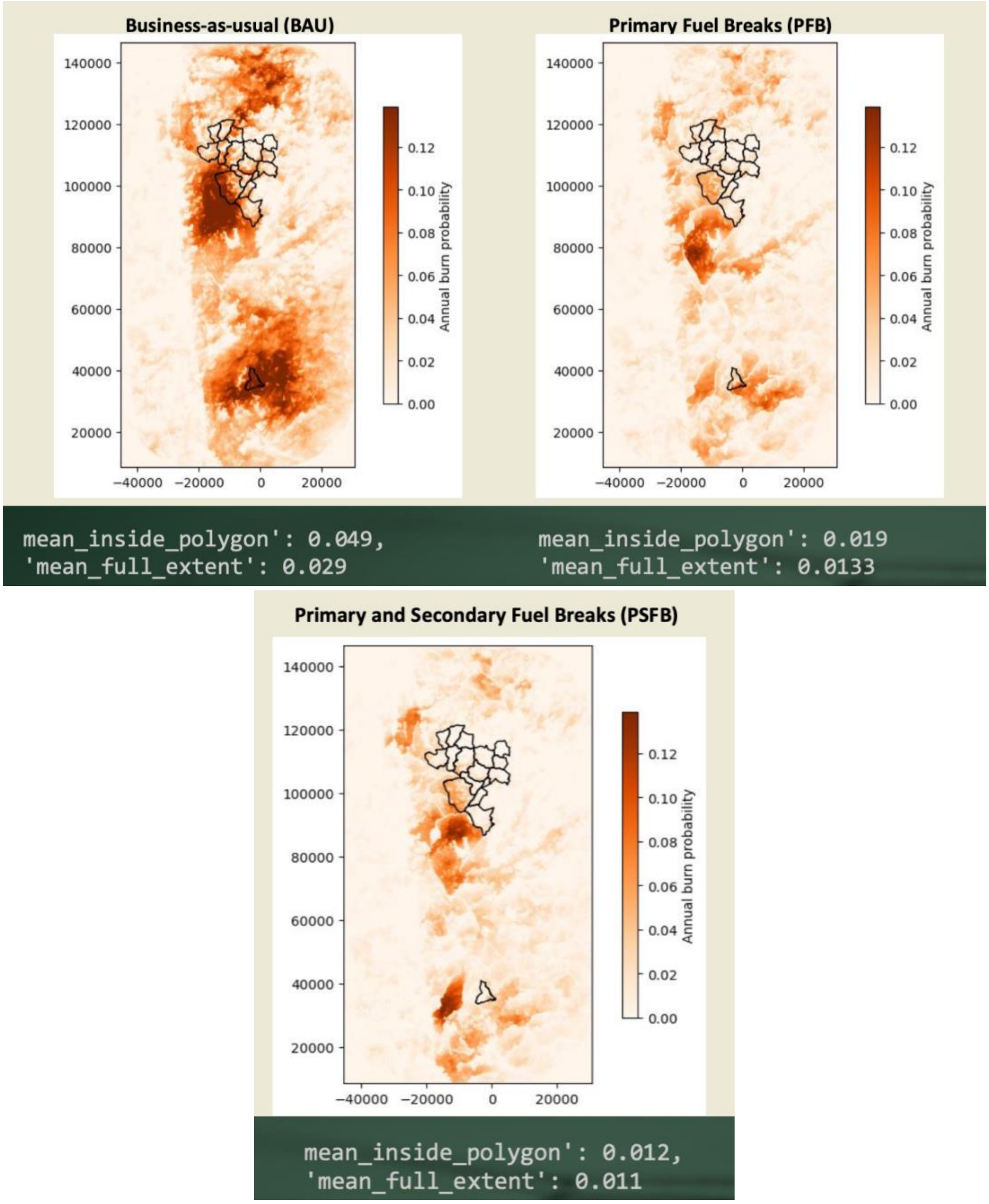

Source: AXA Climate and FMI

Figure 24: Annual burn probability results for the WISE model

Building the new insurance framework

Table 2: Definitions of key terms used in insuranceTable 2 provides an overview of key insurance terms that are used in this section. It should be noted that the metrics used for the purpose of this insurance pricing exercise, in particular regarding the insured value, are indicative and only used for the purpose of the exercise, and do not reflect any clients' asset value. Any insurance premiums are therefore entirely indicative and non-binding.

Of the 16 Areas of Interest (AOIs) in the study area (based on administrative units), all the AOIs do not have the same exposure, with varying levels of forest and building exposures. After various iterations and discussions with local stakeholders, the decision was made to merge all the AOIs and compute one premium. This choice of merging the various municipalities is due to a minimal size effect, given some AOIs have very low exposures and wouldn't be able to be insured independently, as well as to simplify the analysis and visualization by computing one premium instead of 16. The updated final exposure was then computed separately for forests and buildings, where data was collected to build the exposure dataset, including on land cover for studying forest areas, and various building layouts for studying structures.

Forest exposure

The forest layer of planted forests was taken from a publicly available data source from the World Resources Institute (Richter, Goldman, et al., 2024, illustrated in Figure 25). Within the area of interest, the total exposure is 11,957 ha.

Discussions with AGIF were realized to estimate the cost associated with a burned area following which realistic price estimations were received and updated to reflect the actual costs that the insurance could cover, following which a cost of 3350€/ha was chosen for the sum insured.

	Min value (per ha)	Max value (per ha)
Soil stabilization	150€	450€
Cleaning	600€	800€
Replanting	1200€	3500€
TOTAL	1950€	4750€
Proposed Sum Insured (€/ha)	3350 €/ha	

Table 4: Breakdown of sum insured for forest area burned

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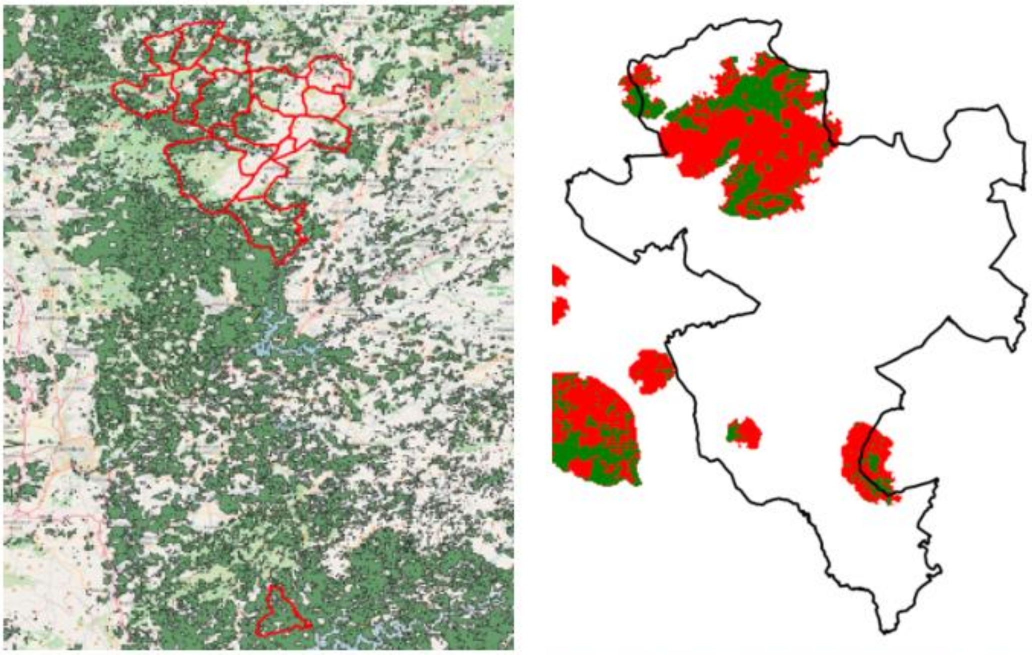

Forest exposure layer (green) with considered AOI boundaries (red).

Illustration of how burned areas are computed. Only the affected exposure falling within the AOI is considered.

Source: AXA Climate

Figure 25: Forest exposure layer (left), and illustration of the burn area computation (right)

To validate the premium computation based on the model outputs, the observed losses were then computed. Using MODIS burned area products[3], annual losses from 2000 to 2023 were estimated. In classic insurance products, pricing would typically be done by fitting a distribution law (Gamma, Weibull, etc.) to the historical losses and calculating the losses based on this fitted distribution. Figure 26 shows the observed losses for the forest as a percentage of the total surface. 2017 can be clearly seen as a year with extreme losses, with 42% of the total surface burned.

[3] https://modis-fire.umd.edu/af.html

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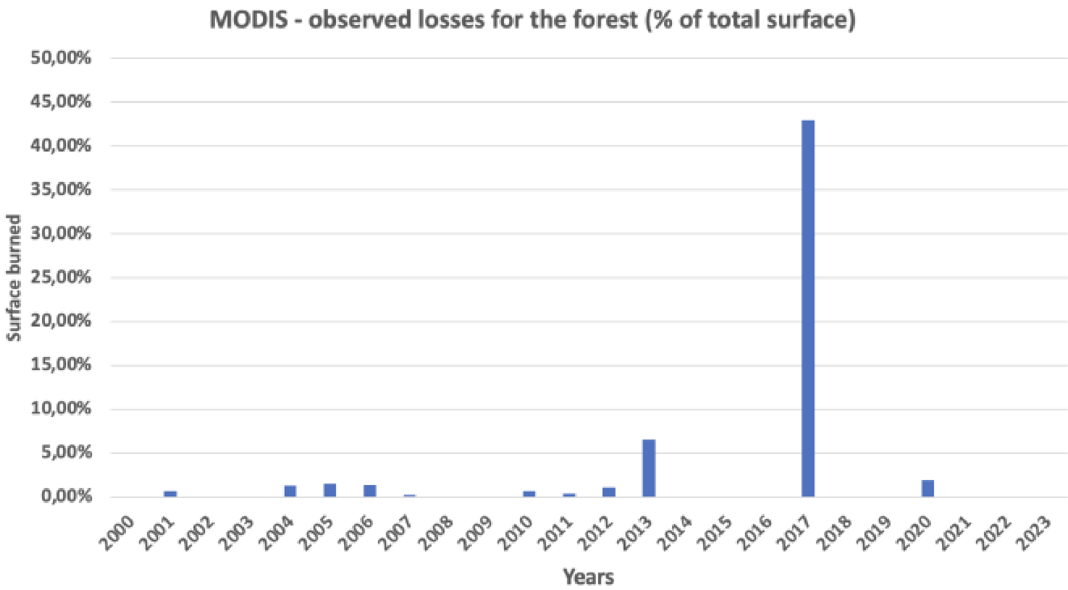
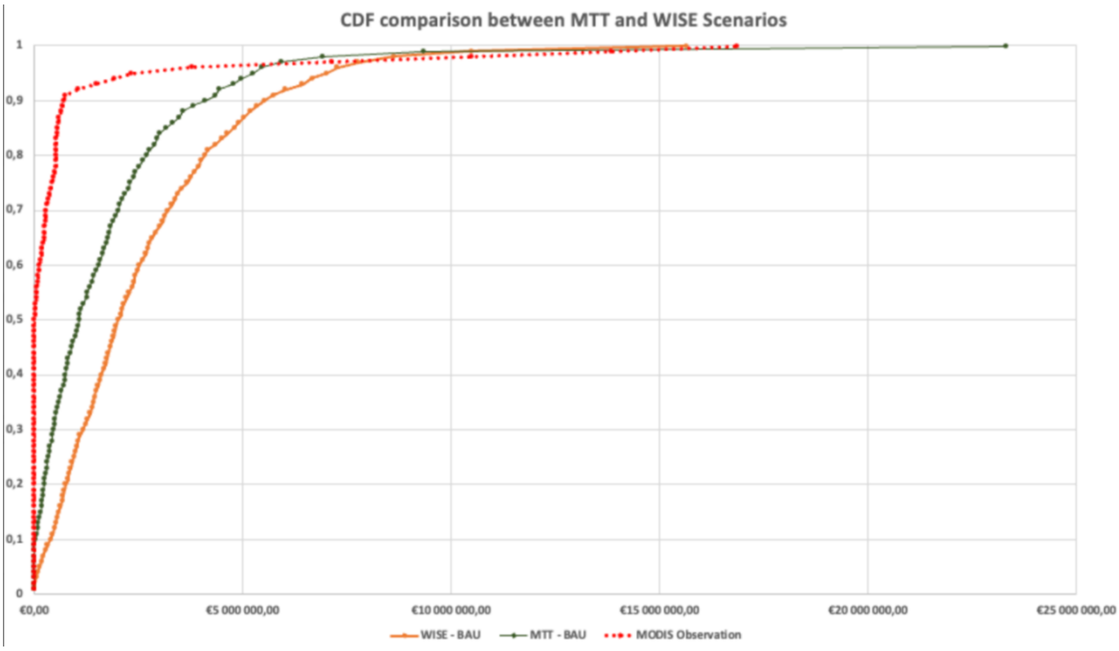


Source: MODIS

Figure 26: Historical observed losses overview

As shown in Figure 27, losses are observed to be higher in the two models when compared to the observations, especially on low and medium severity events. Introducing a deductible and limit to reduce the unused capacity and the maximum payout can potentially mitigate this gap between the observations and the model. There are also various nuances that should be taken into account, as the model was calibrated at a larger scale than the area of interest for the insurance, and the historical losses only have 25 points, compared to a 1000 for the models.



Source: AXA Climate

Figure 27: Comparison of historical observations with MTT and WISE models

Three potential structures were then proposed, depending on how frequently the insurance could trigger, as outlined in Table 5.

Proposed Structure	Frequent Payout	Disaster	Catastrophe
Deductible, % TIV (ha)	5% (600ha)	10% (1200 ha)	15% (1800ha)
Limit, %TIV (ha)	20% (2400ha)	30% (3600 ha)	40% (4800ha)
Sum insured (€/ha)	3350	3350	3350

Source: AXA Climate

Table 5:Potential insurance structures based on payout frequency and intensity

Indicative pricing estimates and premium reductions were then estimated, focusing on the scenarios with complete fuel removal. Table 6 provides a detailed breakdown of the indicative premium reductions across the different models and adaptation scenarios, showcasing very significant premium reductions: **MTT models show reductions of between 43-78% depending on the adaptation scenario and the insurance structure, and WISE models show even more significant reductions, spanning 79-96%.**

MTT											
Insurance structure	Model and adaptation scenario	Deductible			Limit			Indicative Premium	Indicative Premium / ha	RoL	Indicative Premium variation compared to baseline
		TIV percentage	€	ha	TIV percentage	€	ha				
Frequent payout	MTT - BAU	5%	2M	600	20%	8M	2400	1 060 266 €	88,67 €	13,23%	**NA**
	MTT- PFB							603 680 €	50,48 €	7,54%	**43,06%**
	MTT - PSFB							302 668 €	25,31 €	3,78%	**71,45%**
Disaster	MTT - BAU	10%	4M	1200	30%	12M	3600	478 739 €	40,04 €	3,98%	**NA**
	MTT- PFB							267 546 €	22,37 €	2,23%	**44,11%**
	MTT - PSFB							118 471 €	9,91 €	0,99%	**75,25%**
Catastrophes	MTT - BAU	15%	6M	1800	40%	16M	4800	289 522 €	24,21 €	1,81%	**NA**
	MTT- PFB							150 913 €	12,62 €	0,94%	**47,88%**
	MTT - PSFB							62 500€	5,23 €	0,34%	**78,41%**

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WISE											
Insurance structure	Model and adaptation scenario	Deductible			Limit			Indicative Premium	Indicative Premium / ha	RoL	Indicative Premium variation compared to baseline
		TIV percentage	€	ha	TIV percentage	€	ha				
Frequent payout	WISE - BAU	5%	2M	600	20%	8M	2400	2 116 244 €	177 €	26,41%	**NA**
	WISE- PFB							444 072 €	37 €	5,54%	**79,02%**
	WISE - PSFB							228 025 €	19 €	2,85%	**89,23%**
Disaster	WISE - BAU	10%	4M	1200	30%	12M	3600	868 825 €	72,66 €	7,23%	**NA**
	WISE- PFB							84 340 €	7,05 €	0,70%	**90,29%**
	WISE - PSFB							54 635 €	4,57 €	0,45%	**93,71%**
Catastrophes	WISE - BAU	15%	6M	1800	40%	16M	4800	343 899 €	28,76 €	2,15%	**NA**
	WISE- PFB							10 719 €	0,90 €	0,07%	**96,88%**
	WISE - PSFB							13 232 €	1,11 €	0,08%	**96,15%**

Source: AXA Climate

NB: All values in euros are indicative; in this case, the total exposed area is approximately 12,000 ha, focusing on forest exposure

Table 6: Indicative insurance pricing and premium reductions for forest exposure with adaptation across different insurance structures and models (MTT at the top, WISE at the bottom)

Adaptation scenarios also allow the selection of more advantageous product for a same premium. For a fixed deductible, implementing adaptation scenarios enable the customer to increase the limit, fully covering them against dramatic wildfires (which occur less frequently due to the adaptation measures).

As an example, with a 15% deductible (first 1800ha not covered), the maximum payout is about 20% (corresponding to an extra 4800ha burned). By implementing PFB or PSFB, for the same limit it is possible to have a deductible of about 10% (1200ha) or 5% (600ha) (Figure 28).

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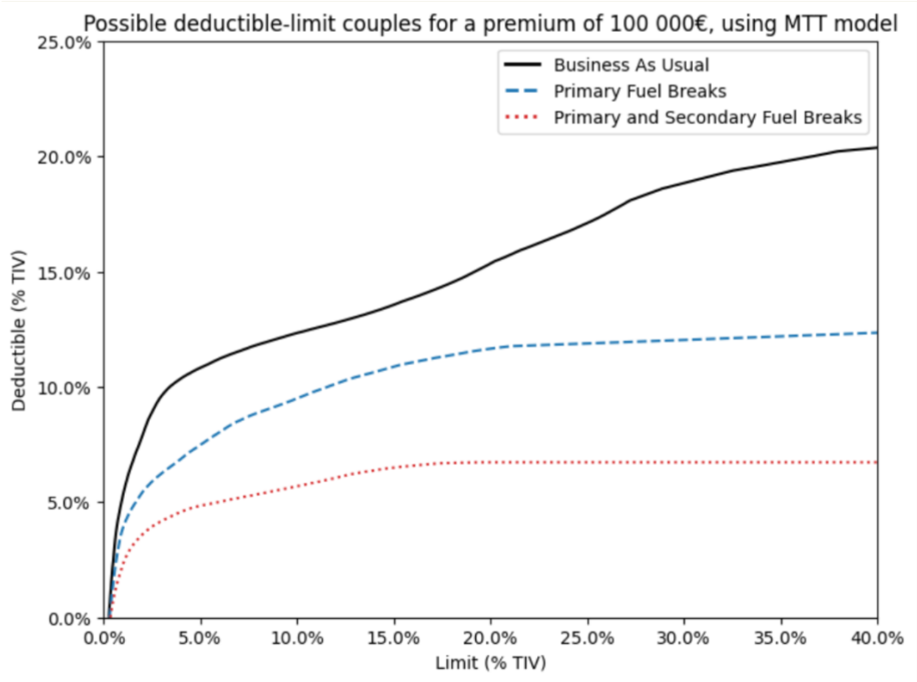

Source: AXA Climate

Figure 28: Possible deductible-limit couples with adaptation measures for the MTT model

When doing a sensitivity analysis to explore scenarios with partial fuel removal, it was seen that while the PFB and PSFB adaptation scenarios were modelled with clear premium reductions visible, the same result is not translated for the PFB-PR and PSFB-PR scenarios with partial fuel removal (with Table 7 providing an illustration on the significant differences in reduction for the MTT model). This stresses the need to create and **maintain** fire breaks to reap the benefits of both adaptation and insurance.

	Variation compared to baseline in annual burned area
MTT PFB	29.48%
MTT PFB-PR	2.7%
MTT PSFB	53.76%
MTT PSFB-PR	8.75%

Source: AXA Climate

Table 7: Premium reduction variations compared to baseline for adaptation scenarios with the MTT model

Building exposure

A first building layer was received from the Portuguese government (Direção-General do Território), which represents the different exposed areas rather than actual buildings. Therefore, using this layer to assess the number or surface of affected buildings would lead to an important over-estimation (as roads, bushes, and gardens are also taken into account). Therefore, a decision to use Overturmaps was made, as the exposure layer emphasizes on the buildings themselves. Figure 29 provides a visual overview of both these maps, as well as an illustration of affected buildings within the burned area for Overturemaps.

The price corresponding to each building was estimated based on the surface and the average price per m^2 in Portugal, taken at 642.5 €/m^2 based on the average taken from Portugal's National Urban Building Evaluation Commission as shared by AGIF. That said, limitations of this approach must be taken into account, as prices can vary from one place to another, and this dataset does not indicate different floors in the building i.e. if there is also a second floor the habitable surface would double, doubling its associated price.

Building exposure layer (in red) with the administrative boundaries (in green).

In pink: buildings' surface extracted from Overturemaps. In red hatches: building layer from Direção-Geral do Território.

In red: an illustrative wildfire. In blue: affected buildings falling within the burned area.

Source: AXA Climate

Figure 29: Building exposure layers (top), and burned area computation illustration (bottom)

Based on the information presented in Table 8, a clear and significant reduction can be seen, showcasing that adaptation scenarios reduce the total affected buildings.

Interestingly, MTT scenarios present a more pessimistic BAU scenario than WISE in this case (which was the opposite previously). This might be due to the differences in the exposure spatial distribution: buildings are more homogeneously located in the AOI, whereas forests are more located in the North-West of the North region.

Insurance type or purpose	Model / scenario	Deductible	Limit		Annual affected value (€)	Variation compared to baseline
		TIV percentage	TIV percentage	€		
Full loss covered	MTT - BAU	0%	100%	2.3B€	**55 592 224€**	NA
	MTT- PFB				**40 389 749€**	27,35%
	MTT - PSFB				**10 756 241€**	80,56%
	WISE - BAU				**25 172 574€**	NA
	WISE - PFB				**10 991 577€**	56,34%
	WISE – PSFB				**3 918 557€**	84,43%

Source: AXA Climate

NB: All values in euros are indicative; in this case, the total exposed area is approximately 3.76M ha, focusing on building exposure.

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Table 8: Indicative insurance pricing and premium reductions for building exposure with adaptation across different insurance structures and models

This methodology does have some limitations which should be taken into account:

- The vulnerability curve is binary (affected/non-affected), which is a strong hypothesis
- No details on the building occupancy could be obtained, which impacts significantly the value at risk or the economic losses.

3.2.3. Loop 3 (October 2025- February 2026)

Loop 3 focused on consolidating technical results, validating them with stakeholders, and exploring pathways for replication and operational development.

Stakeholder Validation and Webinar

In collaboration with the EU Precilience project, a dedicated webinar was organized to present the wildfire modelling framework, adaptation scenarios, and indicative insurance pricing results. The objective was to disseminate the methodology and results to a broader European audience and test its conceptual robustness beyond the Portugal pilot region, and to gather structured feedback from forestry stakeholders, insurers, and climate-service providers through a Mentimeter exercise, the results of which are outlined in Section 2.2.4.

Following the webinar, a dedication work session was held with AXA Climate, AGIF, two forest producer associations active in the pilot region, and municipal authorities from the study region. The session focused on discussing the project progress, receiving feedback, and deliberating possible next steps.

Stakeholders broadly welcomed the approach and expressed strong interest in continuing collaboration beyond the project. Particular attention was given to the structure and specifics of the insurance coverage. The current modelling framework assumes coverage based primarily on replanting and recovery costs, reflecting the preference expressed by forest associations during earlier consultations. However, participants noted that this may not always align with landowner priorities, as some forest owners and managers may prefer coverage focused on timber value loss or wood damage, depending on stand maturity and economic objectives. Although this is something that can be updated with relative ease in the model, it nonetheless highlights the need for flexible product design capable of accommodating different management and ownership profiles.

The maintenance of fuel management strips was identified as a critical determinant of risk reduction effectiveness. While stakeholders agreed on its importance, they emphasized that systematic verification of maintenance remains operationally challenging. The potential use of remote sensing tools for monitoring implementation and compliance was discussed as a promising future avenue, particularly if insurance premium differentiation is linked to adaptation performance.

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A key modelling limitation was also acknowledged: the current wildfire simulations do not incorporate active firefighting interventions. As a result, the model cannot capture the dynamic effects of suppression efforts on final burn extent. While the modelling approach focuses on hazard propagation under given conditions, stakeholders noted that firefighting capacity and response efficiency remain importance for real-world modifiers of impact, which may warrant further research.

Beyond the technical discussion, considerable emphasis was placed on internal communication within government structures and across regional authorities. Participants highlighted the importance of articulating the economic value of adaptation and linked insurance clearly, particularly in demonstrating how quantified burn probability reductions translate into avoided losses, improved resilience, and potential fiscal stability. Developing relevant communication materials and dissemination channels was seen as essential for building awareness, policy uptake, and institutional scaling.

Replicability roadmap

The Portugal pilot developed and calibrated wildfire hazard models integrating adaptation measures directly into risk assessment and indicative insurance pricing. Replication potential exists, particularly in Mediterranean regions facing structural wildfire risk, but depends strongly on governance and adaptation implementation conditions.

In collaboration with LGI, a replicability roadmap was developed, which will be published independently as D4.7 focused on the replicability for all pilots, with a short summary provided below. The replication focus is on the transfer and adaptation of wildfire models to support insurance product design incorporating adaptation in other forested areas across Europe.

Priority actions for post-project replication:

- Re-calibrate wildfire hazard and burn probability models in regions where there is demonstrated need and interest
- Adapt exposure and vulnerability assumptions to local forest types, settlement patterns, and fire regimes
- Assess applicability of the modelling and insurance framework to other Mediterranean contexts with similar climatic and land-use conditions.
- Clarify institutions roles and public-private coordination mechanisms required to operationalize adaptation-linked insurance

Key conditions and dependencies:

- Strong Public-Sector Alignment: Effective collaboration with national or regional wildfire management agencies.

- Adaptation Policy Frameworks: Existence of clearly defined fuel management strategies or prevention networks that can be modelled and monitored.
- Implementation Quality: The effectiveness of adaptation-linked insurance depends directly on the design, execution, and maintenance of fuel management measures in practice.
- Verification Mechanisms: Capacity to monitor and validate adaptation implementation (e.g., via remote sensing).
- Institutional Willingness: Engagement of insurers, forest associations, and public authorities in co-design processes.

Replication horizon: Medium-term, particularly in Mediterranean regions where wildfire risk is structural and adaptation policies are already embedded in governance frameworks. Without robust implementation of adaptation measures, the insurance-adaptation linkage weakens substantially.

3.3. Stakeholder Engagement

Throughout the pilot, extensive engagement was conducted with Portuguese insurance associations, forest organizations, regional authorities, and municipal representatives. These interactions were central to ensuring that the modelling assumptions, valuation methods, and insurance structures remained grounded in operational realities.

Close collaboration was maintained with AGIF and CCDRC (the Regional Commission for Integrated Management of Rural Fires), both of which provided essential data, technical recommendations, and validation of modelling assumptions, and helped facilitating dialogue with additional public and private actors. A structured questionnaire was disseminated to AGIF to better understand their climate service needs and explore how burn probability maps, adaptation scenario outputs, and long-term wildfire catalogues could support planning and decision-making processes. These engagements reinforced the relevance of the modelling outputs beyond insurance design alone, highlighting their value for climate services, territorial planning, and adaptation monitoring.

Discussions with the Portuguese insurance association confirmed strong interest in the wildfire risk maps, burn probability outputs, and adaptation-linked risk reduction metrics developed in the pilot. These were viewed as highly relevant for improving local underwriting practices and supporting risk interpretation. While some stakeholders noted that parametric wildfire insurance may not yet be suitable everywhere in Portugal, there was agreement that the modelling framework and quantified risk reductions could support traditional indemnity products, hybrid structures, or even community-based insurance models. Importantly, it was later clarified that parametric insurance is legally permitted in Portugal, meaning that no regulatory barriers prevent innovation in this space (DLA Piper, 2023).

The forest association of Portugal provided detailed input on preferred insurance coverage structures and territorial aggregation. Stakeholders advocated for insurance pricing at cooperative, OPF (Forest Producers Organization), or ZIF (Forest Intervention Zone) scale to enable risk mutualization and reduce annual volatility. They emphasized that administrative boundaries do not necessarily correspond to actual risk characteristics and may create distortions in pricing. By contrast, cooperatives or other structures could represent operational management units where prevention and adaptation measures are actively implemented.

Forest stakeholders also emphasized that post-fire recovery costs – soil stabilization, cleaning, and replanting- should be prioritized over compensation for lost timber value. They reiterated that the Portuguese forestry sector currently receives no compensation for wildfire-related biodiversity loss, timber loss, carbon stock loss, or ecosystem degradation, in contrast to housing and agricultural sectors. This absence of coverage reinforces the structural vulnerability of forest owners. Regarding willingness to pay, stakeholders indicated that €6/ha is acceptable as a modelling reference value, though final affordability would depend on the scope of coverage and inclusion of both biotic and abiotic risks identified in territorial risk mapping.

Stakeholders also stressed that differentiated premiums could reward active land management. For example, belonging to a ZIF (Forest Intervention Zone) and demonstrating active management could justify lower premiums more than passive ownership. Satellite-based monitoring of fuel management was suggested as a potential verification mechanism.

Regional commissions and municipalities contributed to discussions on spatial aggregation, co-funding options, and integration with broader wildfire governance structures. Questions were raised regarding uneven implementation of fuel management networks across territories and how insurance models could adapt to these differences. These exchanges reinforced the importance of transparent modelling assumptions and adaptive premium updates.

The pilot was also presented across various events to gather responses and input, including:

- Precilience webinar on 9th February, 2026
- Naturance festival on 3rd and 4th February, 2026
- UNEP FI Nature Positive Insurance working group on 5th November, 2025
- Joint Climate DT and PIISA Wildfire webinar - Modelling as a Tool to Understand Wildfire Risk and Risk Reduction Potential, on 13th November 2025
- Adaptive Forest Management and Policy to Tackle Climate Risks Hybrid event, on 11th September, 2025
- OECD roundtable discussion on wildfire risk and insurance, on 28th May, 2025

Overall, stakeholder engagement significantly strengthened the pilot by aligning technical modelling outputs with institutional realities, management practices, and financial constraints.

3.4. Closing remarks

The Portugal pilot demonstrates that adaptation-integrated wildfire insurance is both technically feasible and economically meaningful. The modelling results show that well designed and maintained fuel management networks can substantially reduce burn probability, expected losses, and indicative premiums across both forest and building exposures. In several structures, premium reductions exceed 40-90%, illustrating the potential financial value of prevention. It was also noted that primary fuel breaks are crucial to forests, driving ~60% of total premium reduction, while secondary fuel breaks are the most important measure for households, contributing ~66% of the total premium reduction.

A key finding is that adaptation effectiveness depends strongly on maintenance. Scenarios with partial fuel removal show dramatically lower risk reduction benefits compared to fully maintained fuel breaks. This has direct implications for insurance design: premium reductions must be conditions on verified implementation and maintenance of adaptation measures, a field which has potential for monitoring such activities based on remote sensing methodologies in the future.

A scientific research article is also being prepared alongside this deliverable, which will explain the fire spread modelling and analysis methods in more detail than this report. That paper will also provide several additional findings that could not be included here, and provide a more technical overview of this work.

These pilot results provide a strong foundation for discussions on wildfire adaptation benefits. While implementation and maintenance costs of the adaptation measure were outside the scope of this analysis, future work incorporating annualized treatment costs against annual premium savings would yield a cost-benefit ratio, offering a clearer picture of net benefits. Finally, insurers and risk modelers should integrate these findings into wildfire risk scoring, ensuring that properties benefiting from adaptation and fuel management see that risk reduction meaningfully reflected in their premiums.

4. Conclusion

The PIISA forest pilots demonstrate that climate-sensitive insurance design is both technically feasible and strategically important for European forest resilience.

For the windthrow pilot, the framework shows that combining hazard and exposure data and stand-level vulnerability data to create a Wind Power Exposure Index, which, coupled with historical back-testing and vulnerability maps, enables credible risk quantification for insurance underwriting. The modelling architecture is scalable across regions where high-quality forest and wind data is available, though regional calibration and historical storm validation remain essential prerequisites.

In Portugal, the wildfire pilot demonstrates that adaptation measures – such as primary and secondary fuel management networks – can be explicitly incorporated into hazard modelling. Results show that well-designed and maintained adaptation measures can substantially reduce burn probability and expected losses, with corresponding reductions seen in indicative premiums. Fire spread models both show sharp premium decreases for adaptation scenarios involving primary and secondary fuel breaks considering total fuel removal, with premium reductions up to 70-80% for MTT fire models, and 70-95% for WISE fire models. This confirms that adaptation can generate measurable financial value within insurance structures.

Across both pilots, several overarching lessons emerge:

- Insurance must align with forest management realities with the changing climate
- Regional calibration and ground-truth testing remain crucial to confirm model validity
- Climate services must provide operationally relevant outputs and good usability across audiences
- Adaptation and insurance should be viewed as complementary risk management tools with co-benefits rather than substitutes
- Territorial aggregation enhances feasibility and affordability across larger regions

Replication potential is strong but conditional on enabling environments and local calibration. Scaling these approaches will require continued collaboration between insurers, forest owners, public authorities, and climate service providers. It will also require investment in data harmonization, monitoring of adaptation implementation, and development of hybrid insurance structures where appropriate.

Ultimately, the pilots confirm that integrating climate services, adaptation modelling, and insurance innovation can transform insurance from a reactive compensation tool into a proactive resilience mechanism. This aligns directly with PIISA's objective of strengthening Europe's capacity to manage climate risks through financially and institutionally sustainable solutions.

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Appendices

Appendix 1: Technical Readiness Levels (TRLs)

This section provides an assessment of the Technical Readiness Levels (TRLs) of the Germany and Portugal pilots (PIISA Tasks 3.4.1 and 3.4.2), in line with Horizon Europe TRL definitions. The assessment reflects the start and end TRL as anticipated in the Grant Agreement (GA), as well as the actual TRL achieved by project completion, based on implementation scope and validation activities.

Germany Windthrow Pilot

GA Formulation: Development of a new, comprehensive forest insurance solution covering wildfire, drought, and pest risks in Germany

Start TRL: 3
At project inception, the solution was at TRL 3 (experimental proof of concept). The multi-hazard concept was defined and analytically explored, but not yet demonstrated in a relevant operational environment.

Target End TRL (as per the GA): 6
The Grant Agreement set the objective of reaching TRL 6, corresponding to the demonstration of the technology in a relevant environment.

Actual TRL Achieved: 8 (Reduced Scope - Windthrow)
During implementation, the technical focus was narrowed to windthrow risk, allowing deeper operation development and validation. Based on the activities carried out, the pilot progressed beyond the targeted TRL 6. The insurance product developed with the wind power exposure index was tested with clients and insurers for market placement in Ireland and Scotland. Although the original GA scope was broader (multi-hazard), the windthrow-focused system reached a stage consistent with TRL 8, as the modelling framework and insurance logic were complete, qualified, and tested in a real-world commercial context.

Portugal Wildfire Pilot

GA Formulation: Innovative insurance instruments to support wildfire adaptation measures in Portugal

Start TRL: 2

At project start, the pilot was at TRL 2 (technology concept formulated). The integration of wildfire hazard modelling with adaptation-sensitive insurance mechanisms was conceptual and had not yet undergone structured modelling or validation.

Target End TRL (as per the GA): 3
The Grant Agreement defined TRL 3 (experimental proof of concept) as the target, focusing on model development and conceptual validation.

Actual TRL Achieved: 6
The activities conducted during the project advanced the solution significantly beyond the GA target. TRL 6 (technology demonstrated in a relevant environment) is said to have been achieved as the insurance mechanisms were tested with local authorities under controlled (simulated) operational scenarios. Although the solution was not deployed in a live commercial underwriting environment, it was demonstrated in a relevant institutional context with public authorities and insurance stakeholders. This level of structured validation exceeds experimental proof of concept and aligns with TRL 6.

Appendix 2: Fuel type breakdown in the fire spread models

USDA fuel types	FBP fuel types
Urban	Non-burning
Agricultural	Non-burning
Open water	Non-burning
Bare ground	Non-burning
Low load, dry climate grass	Standing grass
Moderate load, dry climate grass	Standing grass
Low load, dry climate grass-shrub	Standing grass
Moderate load, humid climate grass-shrub	Standing grass
Moderate load, humid climate shrub	Mature Jack or Lodgepole Pine
Low load, humid climate timber-shrub	Mature Jack or Lodgepole Pine
Very high load, humid climate shrub	Mature Jack or Lodgepole Pine
Moderate load, humid climate timber-grass shrub	Boreal mixedwood
Very high load, dry climate timber shrub	Boreal mixedwood
Moderate load broadleaf litter	Boreal mixedwood
Long-needle litter	Immature Jack or Lodgepole Pine
Very high load broadleaf litter	Immature Jack or Lodgepole Pine