The XGBoost model showed weak results when applied in Lesvos, overpredicting harvested areas compared with the GFW (Figure *10*). Part of the reason for the overprediction is that the forests in these two living labs differ. Even though the tree species are similar, the sparse forests on Lesvos, with open canopies where the ground is visible in the satellite image, are not common in the NOW-SW LL. Therefore, neither model has been trained to recognize those signals as forest and can easily consider them as a "disturbance". Even the ResNEt model that uses a time series tends to show those areas as non-forest. To improve the performance, the models should be retrained with local field data.

Figure 10: Results from Global Forest Watch loss in red (left) and predictions of harvested areas using the XGBoost in yellow (right)

2.2 Innovative methodologies for fuel structure assessment

2.2.1 Background and previous work

Fuel load Assessment in Catalonia Living Lab

This work builds upon the developments presented in Deliverable D2.1, where INRAE's methodology for vegetation fuel characterization directly from LiDAR data was established. That deliverable laid the conceptual and methodological foundations for a workflow capable of estimating key fuel parameters such as canopy base height (CBH), canopy bulk density (CBD), and canopy fuel load (CFL), among others, from ALS point clouds without relying heavily on field calibration data. This work is also described in the scientific paper: *Unlocking the potential of Airborne LiDAR for direct assessment of fuel bulk density and load distributions for wildfire hazard mapping*. (Martin et al. 2024). The present deliverable represents the continuation of that effort, focusing on the implementation and validation of the methodology within the Catalonia Living Lab during the year 2025.

The main objective of this phase is to test the implementation of an operational workflow of the methodology using regional ALS datasets, evaluate its performance under regional conditions, and identify the challenges and refinements needed to produce reliable fuel metrics at landscape scale. Through this implementation, the workflow was adapted, tested, and validated using the available LiDAR and field data, providing valuable insights into its robustness and applicability beyond the initial test sites used in the French context.

The Catalonia Living Lab benefits from comprehensive LiDAR coverage through the LiDARCAT3 dataset, which provides a consistent and detailed representation of the territory. The point cloud density is comparable to the French ALS data used by INRAE, averaging around 10 points/m², with most areas reaching up to 12 points/m² and only a few dropping to around 8 points/m². This distribution of density and the coverage of Catalonia are shown in the Figure 11. As the image below displays, this high-density coverage spans the entire region, ensuring a homogeneous spatial dataset suitable for large-scale fuel characterization. Moreover, a new LiDAR survey is currently underway, ensuring that the dataset is regularly updated and temporally maintained, making it a potential tool for long-term environmental monitoring and fire managing.

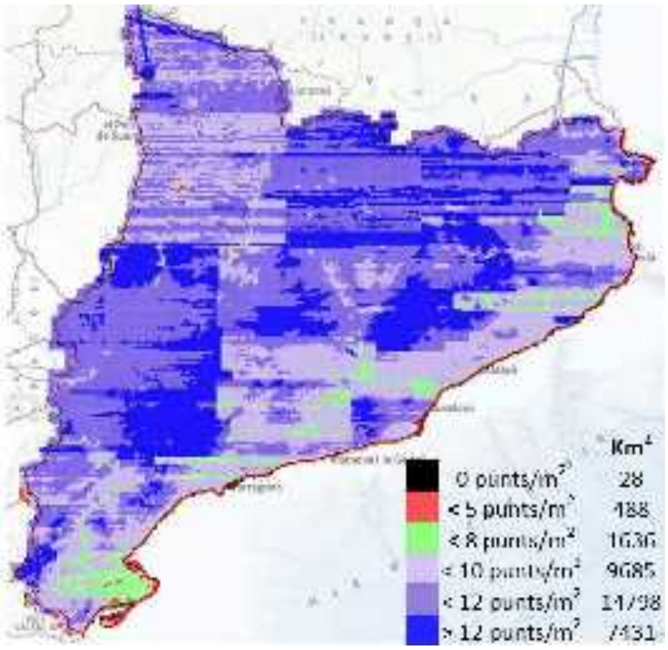

Figure 11. Catalonia's LiDAR coverage and point density.

This context provides an ideal framework for applying and testing the INRAE methodology, enabling both the validation of the approach under diverse Mediterranean landscapes and the preparation of a scalable workflow for continuous fuel mapping and wildfire risk assessment in Catalonia.

Developed Methodology

As commented before, the methodology to estimate the fuel load was developed by INRAE in the context of IA. 2.1 and it's detailed in Delivery 2.1. Figure 12 represents the workflow and the main characteristics of this methodology.

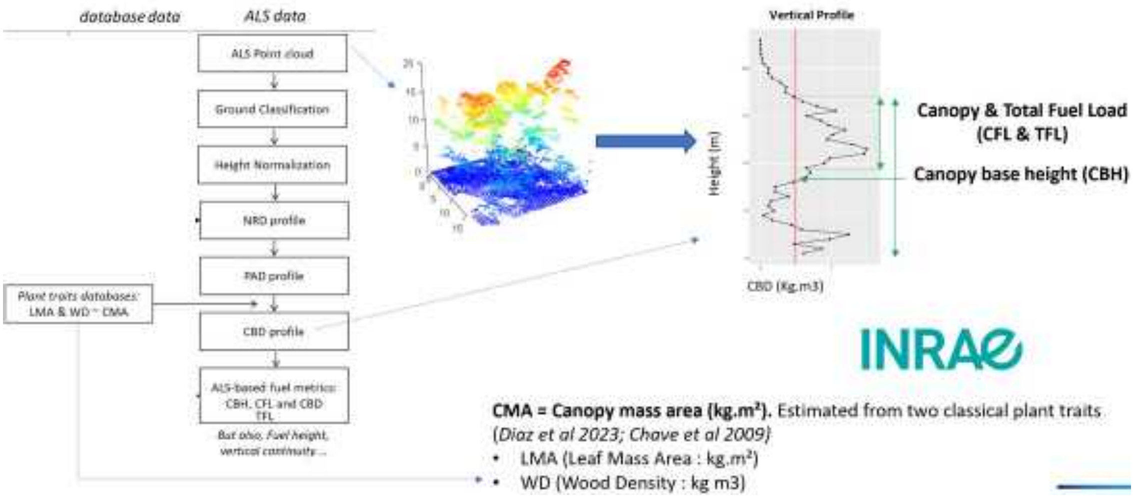

Figure 12. Methodology workflow. From the point cloud to Canopy Bulk Density (CBD) profiles and fuel metrics.

This work presents an innovative methodology for deriving vegetation fuel characteristics directly from airborne laser scanning (ALS) point clouds, avoiding reliance on field data or classification models. The approach is designed to be broadly applicable, accounting for heterogeneities in sampling, sensor types, flight patterns, and vegetation structures, thus ensuring wide transferability across contexts.

The method produces complete vertical canopy bulk density (CBD) profiles, from which multiple fuel properties can be derived, including canopy base height (CBH), canopy fuel load (CFL), and CBD, as well as other descriptors such as vertical fuel continuity and fuel strata gaps.

Validation with field data from France and Portugal confirms the robustness of ALS-based estimates. Comparisons show strong consistency between ALS-derived metrics and expert field assessments of vegetation structure and fuel characteristics, reinforcing the reliability of this approach for quantifying fuel structure at different heights.

The entire processing chain has been implemented in R, allowing efficient integration with existing LiDAR analysis tools and enabling large-scale applications. These results form the foundation of a forthcoming scientific publication.

2.2.2 Methodology implementation within Catalonia Living Lab

Field Campaign

Field data collection within the Catalonia Living Lab was conducted to provide reference information for the validation of ALS-based fuel metrics. A total of 60 plots were established across nine sub-climate zones, ensuring representation of the environmental variability that characterizes the study area. Figure 13 presents the distribution of the field plots across Catalonia and a closer view of one of the sampled sub-zones and its field plots.

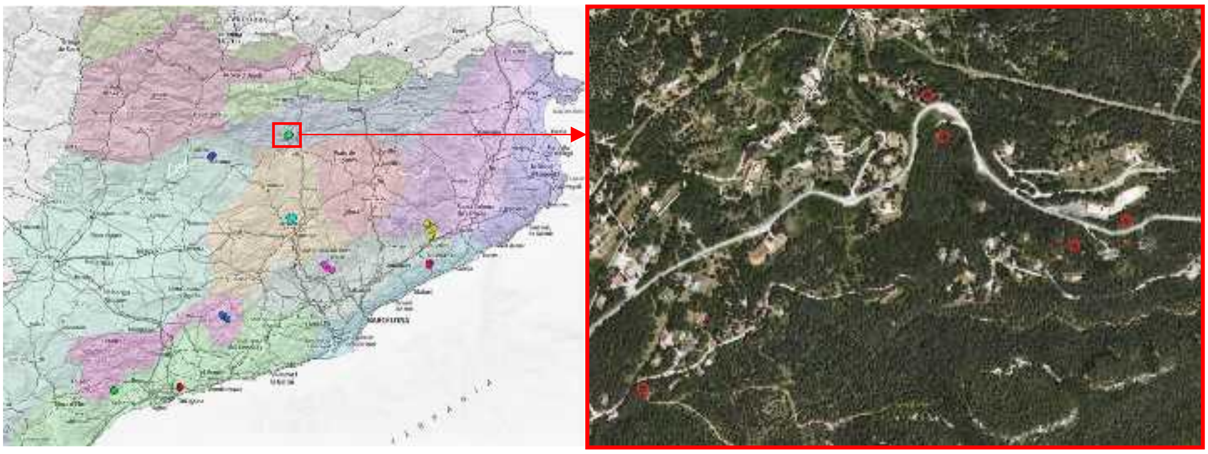

Figure 13. Left, distribution of the groups of plots, background Catalonia's sub-climate zones. Right, example of the distribution of plots in a selected zone.

Each plot was defined as a circular area with a 10-meter radius, where all trees and shrubs were systematically inventoried. Within these plots, detailed measurements were taken, including canopy base height (CBH), shrub height, species identification, vegetation cover, and stem diameter. These variables provide a comprehensive description of the vertical and horizontal structure of vegetation, essential for assessing fuel characteristics. Figure 14 shows images of the fieldwork, highlighting the technicians' activities and the diversity of vegetation surveyed.

Figure 14. Pictures of the fieldwork. From left to right, marks of the center point of the plot and its axis; canopy base height measurement; tree's diameter measurement.

The field data serves not only to describe vegetation composition and structure but also to derive key fuel metrics. To this end, the subcontracted company applied allometric algorithms to compute fuel load from the surveyed parameters, ensuring standardized and comparable outputs across the different zones. This information was then used to evaluate the reliability of the ALS-derived metrics.

Model Validation

Model validation in the Catalonia Living Lab relied on field measurements collected during the campaign, which provided an independent reference to assess the reliability of the ALS-based estimates. Two parameters were selected for this purpose: fuel load and tree count.

The comparison between ALS-derived outputs and ground data showed a model adjustment with an R^2 of 0.52 for fuel load and 0.68 for tree count (Figure 15). These values indicate that the methodology can capture the main trends in fuel characteristics and stand density, while also highlighting the challenges inherent in modeling highly heterogeneous Mediterranean vegetation.

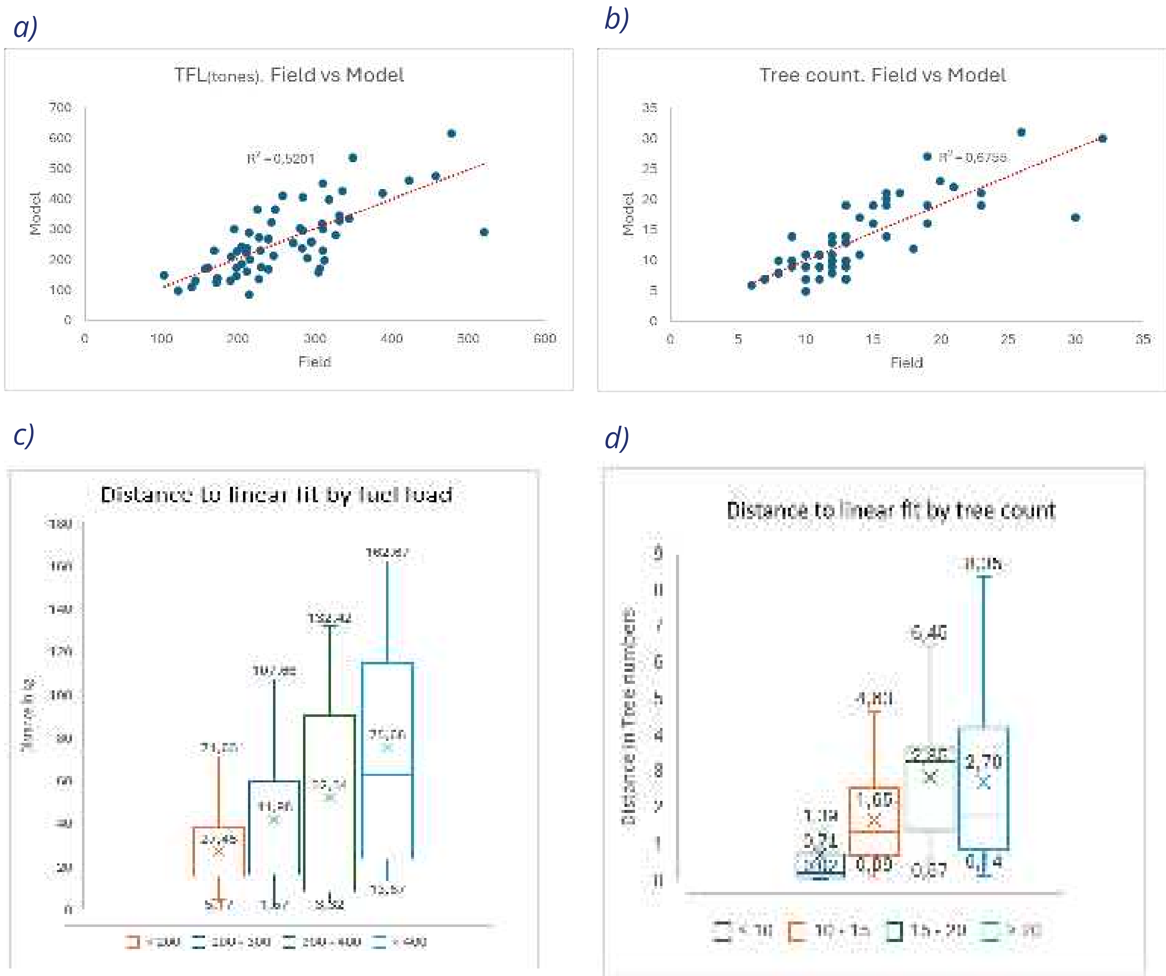

Figure 15. Results of evaluation of the model in Catalonia LL. a) Scatterplot of Fuel vs Model for fuel load. b) Scatterplot of Fuel vs Model for tree count. c) Boxplot of the distance to the linear fit of the scatterplot by fuel load groups. d) Boxplot of the distance to the linear fit of the scatterplot by number of trees groups.

The analysis further revealed that model performance varies according to stand conditions. Plots with lower tree density and reduced fuel accumulation tended to show better agreement between ALS estimates and field observations. This suggests that the methodology is particularly effective in structurally simpler environments, where the vertical distribution of vegetation is easier to characterize and occlusion effects are less pronounced. By contrast, in denser plots the model adjustment decreases, likely due to the increased complexity of canopy layering, overlapping vegetation strata, and limitations of LiDAR penetration in closed canopies. There were no significant differences in the adjustment between different climate zones.

These findings indicate that the methodology provides reliable estimates of fuel and structural parameters, especially in open and moderately dense stands, which are frequent in Mediterranean landscapes. However, they also underline the need of more detailed information (labeling the points by species, wood density, leaf mass area) for more complex forest structures, where multiple vegetation layers and higher biomass complicate the direct retrieval of fuel characteristics. The results confirm its capacity to support large-scale fuel estimation in diverse environmental conditions.

Test Results and future steps

The implementation of the model within the Catalonia Living Lab data was successfully achieved through the development of a dedicated workflow that integrates the R packages associated with the methodology. This workflow was designed, tested, and proved functional, allowing the direct derivation of fuel characteristics from ALS point clouds.

The first results obtained provide a visually coherent and detailed representation of vegetation structure across the study area. For comparison, images in Figure 16 display the orthophoto and the corresponding fuel load (10 m pixels) of the same area, overlaid with a red 1 km–sided grid, to demonstrate the visual comparison.

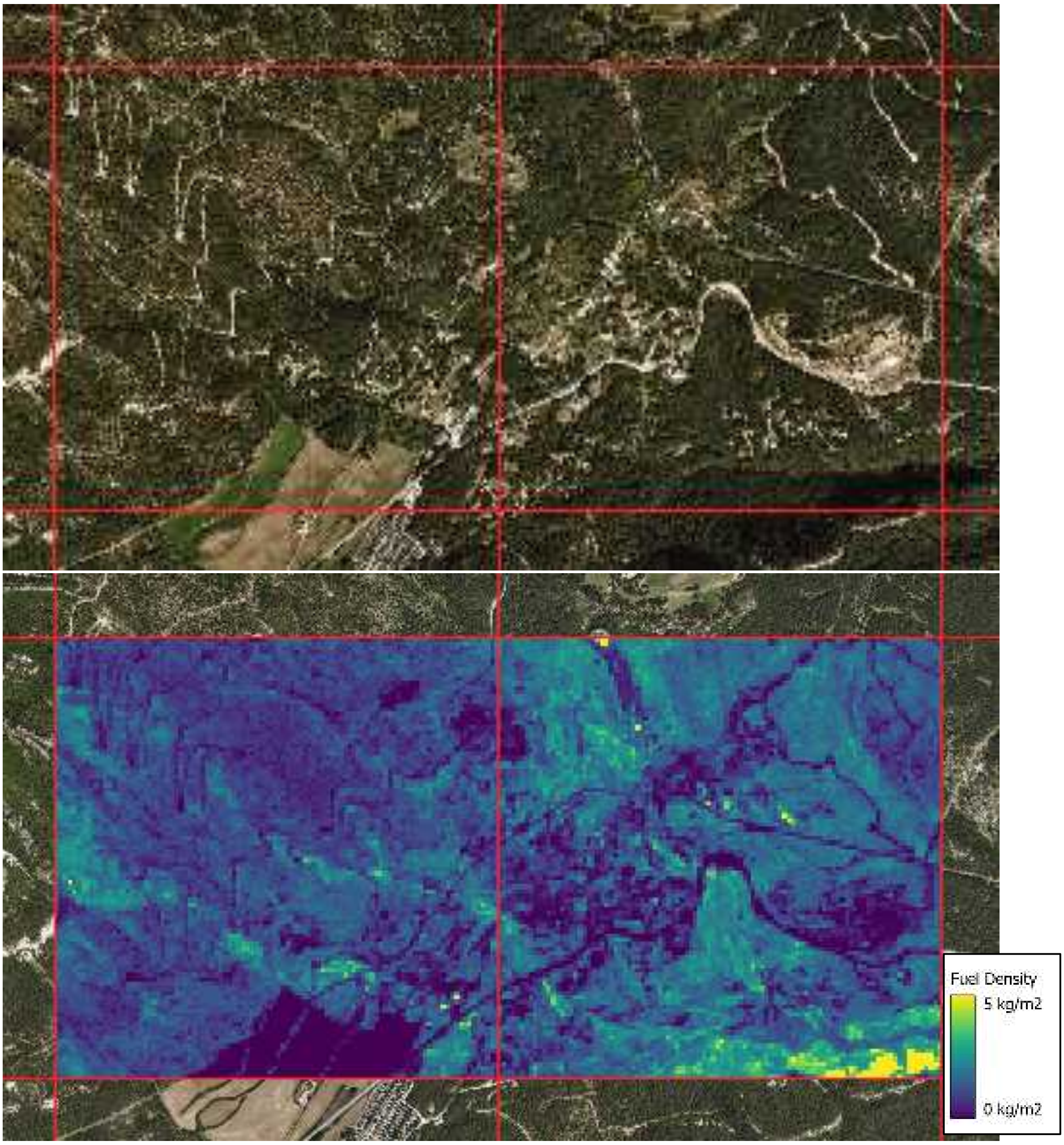

Figure 16. On top, ICGC's orthophoto 25x25cm pixel. Below, fuel model results 10x10m pixel. Both with a 1x1km grid as reference.

Despite these results, some limitations were detected that require further refinement. Errors and miscalculations appeared particularly in areas with steep slopes, ridges, or overhanging terrain, where geometric distortions and occlusion effects can alter the distribution of LiDAR returns. As an example, Figure 17 shows a 1×1 km plot from the model, highlighting a serpent-like trail of pixels with fuel loads exceeding 17 kg/m^2. These pixels correspond to a rocky, low-vegetation zone that should have values close to 0 kg/m^2, located on a mountain cliff. Comparing the slope map with the fuel model reveals a clear relationship between these likely error zones and areas with the steepest slopes.

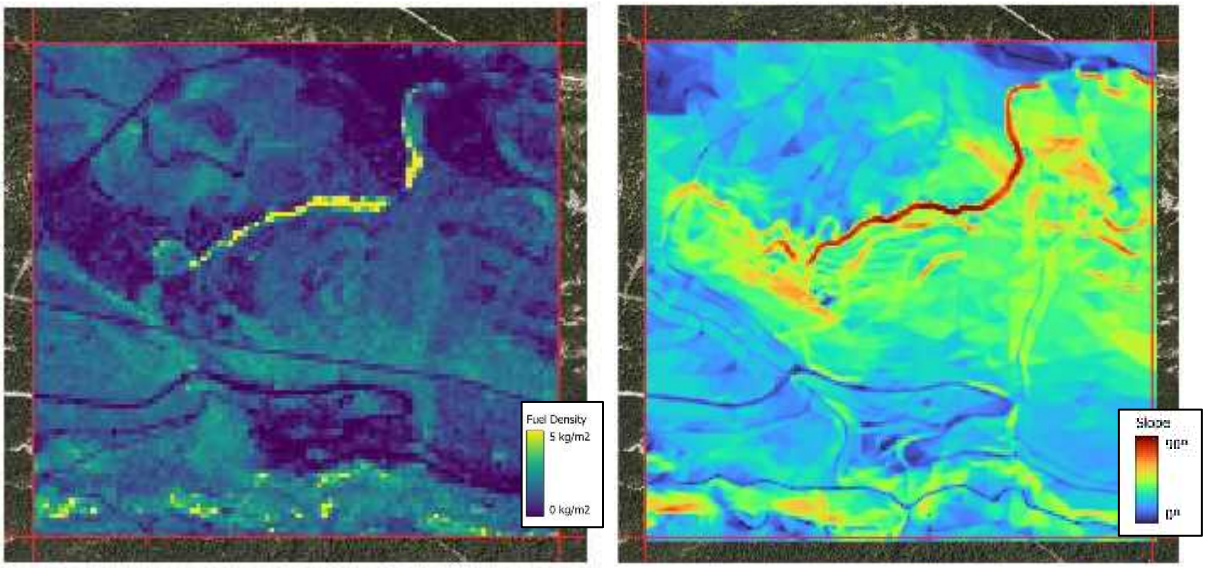

Figure 17. In the left, tile with fuel model results, the saturated pixels correspond to an error due to the geometric distortions. In the right, tile with the slope map, clearly showing the shape corresponding to the mountain cliff.

Once these corrections are implemented, the next priority will be to strengthen the validation process by expanding the comparison with ground truth data. This step will be essential to ensure the reliability of the outputs and to move towards the generation of a robust, operational product that can be deployed at larger scales for fuel monitoring and fire management purposes.

3. Closing remarks

3.1 A dynamic high-resolution map of the state of the forest and fuel

The operationalization of a live, automated process for change detection using satellite imagery presents several practical challenges that extend beyond purely research-oriented concerns. These factors must be acknowledged, as they can significantly influence the reliability, efficiency, and interpretability of the results.

Key considerations include:

- **Image Selection Strategy**: Choosing which Sentinel-2 images to process is critical. A stricter filtering threshold may reduce false positives, but it risks having insufficient observations and missing relevant changes. Conversely, using all available images increases computational load and the likelihood of artifacts or misclassifications.

- **Masking and Preprocessing Challenges**: Effective masking, such as clouds, water bodies, or forests, helps to reduce noise on the final product. However, they are also another source of uncertainty and potential error, for example, where clouds are not masked and are misinterpreted as land cover changes, or if valid land features are mistakenly masked, excluding real changes.

- **Post-Processing**: Post-processing decisions such as sieving, consistency rules, etc, directly affect the results. Additionally, multiple Sentinel-2 images can be acquired from the same date but different orbits, which may introduce inconsistencies or require alignment strategies and should be addressed as part of the process.

- **Algorithm Overlap and Conflicts**: When using multiple algorithms, some can produce outputs for the same area, creating contradictory results. Establishing a method to reconcile or prioritize results is essential to avoid ambiguity.

- **Technical and Operational Uncertainties**: Potential issues, such as pixel misalignment, satellite orbit shifts, or sensor anomalies, might arise with time and introduce errors that are difficult to detect and correct within an automated workflow. Although validating a near-real-time process is challenging, it is essential to incorporate some quality checks into the process.

The dynamic high-resolution map developed in subtask 2.1.1 represents a significant step toward providing timely, landscape-level insights for wildfire management. Its value lies in its ability to reflect the current state of the forest and fuel conditions, which is essential for informed decision-making across all phases of wildfire response—from prevention and preparedness to active firefighting and recovery.

Future work should focus on enhancing the robustness and operational reliability of this mapping system. Some areas for improvement include masking accuracy (e.g., clouds, water bodies, forest cover), refining the post-processing, and integrating validation mechanisms to ensure that the maps accurately reflect on-the-ground conditions. As the system evolves, additional data sources can be incorporated into the workflow, along with new algorithms for handling other types of changes. User feedback will be key to maintaining its relevance and utility towards a wildfire-resilient landscape.

3.2 Innovative methodologies for fuel structure assessment

The implementation of the ALS-based fuel characterization model in the Catalonia Living Lab demonstrates both the feasibility and the potential of this innovative approach. The workflow developed with R packages successfully produced detailed outputs that visually capture vegetation structure and fuel distribution across diverse sub-climate zones. These results highlight the capacity of the methodology to provide valuable insights into wildfire-related fuel metrics at landscape scale.

The evaluation of model fitting showed that it successfully captures the general trends of fuel load and stand density across the Living Lab. Performance is stronger in open or moderately dense stands, where structural complexity is lower and the LiDAR signal can be more effectively translated into vegetation attributes. In contrast, in denser zones the accuracy decreases, revealing the need for complementary information such as precise tree species, leaf mass area, or other traits that influence canopy bulk density. Interestingly, no significant differences were observed between sub-climate zones, which suggests that the methodology can be applied consistently across varied environmental conditions.

At the same time, geometric distortions in steep slopes, ridges, and rocky outcrops emerged as a clear limitation that must be addressed in order to avoid systematic errors in these areas.

Future work will therefore focus on refining the methodology to correct for these distortions and improve model fitting in structurally complex stands. In parallel, validation will be expanded with additional ground truth data, providing stronger support for the generation of a reliable and operational product. Once these improvements are achieved, the workflow will be ready to support fire risk assessment, fuel monitoring, and forest management strategies in Catalonia Living Lab.

3.3 Technology Readiness Level Achieved

This deliverable shows the implementation of a framework for updating high-resolution fuel maps using near-real-time change detection in satellite data, along with the demonstration of the methodology for deriving vegetation fuel characteristics directly from ALS. Together with the results presented in D2.1, they confirm that the proposed technology has been effectively demonstrated in a relevant environment and IA2.1 has successfully achieved the expected Technology Readiness Level 6 (TRL6).

4. References

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