

Mapping Fuel Categories in Mediterranean Regions with Sentinel-2 and PlanetScope Satellite Acquisitions

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Abstract

Accurate and spatially explicit mapping of forest fuel types is essential for developing integrated wildfire risk management strategies, estimating fire danger, and modeling fire propagation in fire-prone Mediterranean ecosystems. While time series of Copernicus Sentinel-2 multispectral imagery at 10 m spatial resolution have proven effective for regional fuel mapping, severe spectral and spatial ambiguities persist in distinguishing complex canopy structures, heterogeneous shrublands, and pastures. This study explores the synergistic integration of Sentinel-2 time series and high-resolution PlanetScope satellite acquisitions (3 m spatial resolution) to produce a 10 m fuel type map (9 classes) over a pilot area in Sardinia, Italy. A total of 114 features were synthesized, combining dynamic Sentinel-2 metrics (kNDVI, FAPAR, NDMI, ReNDVI harmonics), PlanetScope seasonal kNDVI zonal statistics and Gray-Level Co-occurrence Matrix (GLCM) textural features, and static terrain/canopy parameters. Using an XGBoost machine learning classifier trained on 245 photo-interpreted Regions of Interest (80/20 spatial split), three sets of features were compared. The combined model achieved a test overall accuracy of 74.46%, compared to 74.05% for Sentinel-2 alone and 74.66% for PlanetScope alone. Notably, incorporating PlanetScope textural features significantly improved classification metrics for dense canopy classes, increasing the F1-score of broadleaf evergreen trees and needleleaf evergreen trees. The PlanetScope GLCM kNDVI autumn entropy emerged as the most important feature overall. Conversely, PlanetScope performed poorly on the grass class. These findings highlight the critical trade-offs and high complementarity between fine spatial texture and broad spectral coverage for operational wildfire management.

1. Introduction

Wildfires represent one of the most critical environmental hazards threatening ecosystems and human communities across the European Mediterranean Basin. Mediterranean regions in Portugal, Spain, Italy, France and Greece are experiencing intensified fire regimes characterized by larger burned areas, higher severity, and more frequent extreme fire events driven by rising temperatures, prolonged droughts (Feron et al., 2026), and landscape-scale vegetation accumulation resulting from agricultural abandonment (Assini et al., 2015). In Sardinia, Italy — the second-largest island in the Mediterranean Basin — wildfires annually impact thousands of hectares of Mediterranean forests, shrublands, and rural landscapes. Effective wildfire management strategies, including pre-fire hazard assessment, real-time fire propagation modeling, and post-fire severity mapping, rely fundamentally on the availability of accurate, up-to-date, and high-resolution spatial data on fuel types. Fuel mapping is key to fire propagation risk assessment and regeneration potential (Aragoneses et al., 2021). It provides the baseline structural input required by fire behaviour simulators (e.g., Rothermel-based models) to estimate rate of spread, flame length, and crown fire potential, or by fire emission models. Beyond their role as inputs to fire models, fuel maps can also support land managers in identifying areas where fuel treatments and other management activities may be prioritized to reduce wildfire hazard and to improve prevention and planning. Traditionally, fuel type mapping relied heavily on field inventories and manual photointerpretation of aerial imagery. While field surveys provide high local detail, they are labour-

intensive, costly, logistically constrained in rugged terrain, and difficult to update frequently at regional scales. Over the past decade, satellite remote sensing has revolutionized fuel mapping by providing multi-spectral, multi-temporal, and continuous coverage of land surface dynamics. In particular, the Copernicus Sentinel-2 constellation delivers imagery, acquired by the optical Multispectral Instrument (MSI), at 10–20 m spatial resolutions with a 5-day revisit time, under optimal conditions. Apart from visible and near-infrared (NIR) spectral interval, Sentinel-2 features specific radiometric bands in the Red-Edge (705–783 nm) and Short-Wave Infrared (SWIR, 1610–2190 nm) regions, which are sensitive to leaf chlorophyll content, canopy structure, and leaf equivalent water thickness. Recent studies have leveraged dense Sentinel-2 time series to map fuel types across Mediterranean landscapes. By fitting harmonic trigonometric functions to time series of vegetation indices (VIs), such as NDVI, ReNDVI, and NDMI, researchers can capture key phenological parameters, including seasonal amplitude, baseline mean, and timing of phenological phases (green-up and senescence), that distinguish major vegetation covers (e.g., broadleaf deciduous forests, broadleaf evergreen maquis, coniferous stands, and herbaceous vegetation). In a previous study conducted for a pilot region in western Sardinia covering Sentinel-2 tile 32TMK (~10000 km²), Rajabi (2024) adapted the European H2020 FirEurisk hierarchical fuel classification system (Aragoneses et al., 2023) to local Mediterranean vegetation. Applying Support Vector Machines (SVM) and Gradient Tree Boosting (GTB) models to Sentinel-2 VI harmonic parameters, topographic factors, and canopy height metrics derived from Google Earth Engine (GEE), the work achieved promising overall test accuracies exceeding 75%.

However, that work revealed classification bottlenecks: i) significant misclassification occurred between structurally similar woody classes, such as low-growing broadleaf evergreen trees (i.e., *Quercus ilex*, *Quercus suber*, *Olea europaea*) and tall, dense shrublands (i.e., *Arbutus unedo*, *Pistacia lentiscus*, *Erica arborea*); ii) large spectral overlap was observed between dry, senescent pastures and open herbaceous crops during late summer; iii) the 10 m spatial resolution of Sentinel-2 pixels frequently created "mixed pixel" signatures in fragmented Mediterranean landscapes where forest, garrigue, herbaceous vegetation and bare soil form intricate mosaic patterns. Regarding this last point, these classification challenges are for instance relevant in the open agro-silvo-pastoral landscapes of Sardinia (similar to those of the Iberian Peninsula commonly referred to *dehesa* in Spain and *montado* in Portugal), where sparse evergreen oak canopies are interspersed with pastures and crops.

To overcome the spatial resolution constraints of 10 m satellite sensors, recent remote sensing research has turned to commercial micro-satellite constellations. PlanetScope, operated by Planet Labs, consists of over 300 nanosatellites that acquire daily multispectral imagery at a spatial resolution of 3 m. Its DOVE and SuperDOVE sensors provide optical coverage across visible, Red-Edge (on SuperDOVE), and NIR bands, allowing the extraction of high-resolution spatial texture and fine canopy spatial metrics. While PlanetScope offers nearly daily 3 m observations, its data processing presents some technical challenges, including inter-cube radiometric inconsistencies, sensor-specific calibration variations, absence of SWIR bands, and high-frequency noise levels requiring rigorous atmospheric, cloud, and terrain shadow pre-processing. Building directly upon the work by Rajabi (2024) and incorporating advanced pre-processing workflows developed for PlanetScope time series, this work presents scientific advances. The primary goal of this work is to explore and evaluate the synergistic combination of Sentinel-2 multi-spectral time series and high-spatial-resolution PlanetScope acquisitions for regional-scale (10 m grid) fuel type mapping in Mediterranean ecosystems. Specifically, this paper: i) synthesizes an extensive multi-sensor features set (consisting of 114 features) encompassing dynamic multi-spectral harmonic metrics, seasonal kernel NDVI (kNDVI) (Camps-Valls et al., 2021) zonal statistics, high-resolution Gray-Level Co-occurrence Matrix (GLCM) textural metrics, and static terrain/canopy structural features; ii) implements a supervised XGBoost machine learning model with a strict 80/20 spatial patch split to evaluate three sets of features to distinguish fuel types: Sentinel-2 + static, PlanetScope + static, and Sentinel-2 + PlanetScope + static; iii) quantifies class-specific performance metrics (F1-score, precision, recall) across eight fuel classes; iv) evaluates feature importance rankings to determine the relative diagnostic contributions of high-resolution spatial texture derived from PlanetScope images versus Sentinel-2 multi-spectral temporal phenology for operational wildfire management.

2. Study area

2.1 Study area

The study area encompasses the island of Sardinia, Italy, focusing specifically on a representative regional pilot site defined by the Copernicus Sentinel-2 grid tile named 32TMK. Sardinia is located in the central-western Mediterranean Sea and is characterized by a complex Mediterranean landscape shaped by varied topography, centuries of pastoral and agricultural activities, and a predominantly Mediterranean climate under the

Köppen–Geiger classification, characterized by hot, dry summers and mild, relatively wet winters, but with marked spatial variability associated with the island topography and latitude, including a transition from Csa to Csb conditions in the higher inland areas.

The Sentinel-2 tile 32TMK covers a fixed ground extent of about 12,000 km² in western-central Sardinia, stretching from approximately 7.82° E, 39.66° N in the southwest to 9.12° E, 40.65° N in the northeast. The tile encompasses diverse topographic and phytoclimatic gradients, extending from sea level along the Gulf of Oristano and the western coastal plains up to rugged interior mountain massifs exceeding 1,000 m above sea level.

Sardinia island frequently experiences wildfires during the summer months, mostly driven by both arson and accidental causes. Large wildfires (>100 ha) accounted for only 2.5% of all fire events recorded between 1998 and 2019 yet were responsible for 57.6% of the total area burned, thus highlighting the significant contribution of a small number of large events to the regional wildfire regime (Salis et al., 2023).

According to regional land cover inventories, approximately 50% of the territory is covered by natural and semi-natural vegetation that functions as wildland forest fuel, described below.

Broadleaf Forests (~23%): Forests dominated by Mediterranean oak species, with evergreen oaks (i.e.: *Quercus ilex*, *Quercus suber*) prevailing at lower elevations, and deciduous oaks (*Quercus congesta*, *Quercus pubescens*) more common in cooler and higher areas. *Castanea sativa*, *Taxus bacata* and *Ilex aquifolium* can be also found in the highest mountains. **Mediterranean Shrubs and Garrigue (~27%):** Highly heterogeneous, multi-layered fuel complexes ranging from low coastal garrigue to dense, tall maquis exceeding 3 m in height. Due to rural land abandonment, these shrublands are undergoing progressive secondary succession into high-fuel-load maquis and dense broadleaf forest stands. **Coniferous Forests (~2%):** Primarily located along coastal dunes and low hills, mainly consisting of historic reforestation plantations of *Pinus halepensis* and *Pinus pinea*. **Herbaceous Agriculture, Pastures, and Grasslands (~40%):** Dominates the western plains (i.e., Campidano) and rolling agricultural foothills, comprising annual cereal crops, dry pastures, and natural annual grasslands. **Permanent Crops (~3%):** Vineyards, olive groves, and orchards. **Urban Infrastructure & Non-vegetated (~4%):** Built-up settlements, road networks, open water bodies, and bare rock outcrops.

2.2 Target Fuel Classification System

This study adapted the hierarchical fuel classification system of the European H2020 FirEurisk project to the specific ecological and structural conditions of Mediterranean Sardinia. The FirEurisk system establishes a standardized, multi-level fuel taxonomy (Aragoneses et al., 2023) designed to harmonize fuel mapping across European pilot sites. While the first level provides continental-scale fuel categories at 1 km resolution, this study targets a refined pixel-level classification at 10 m spatial resolution.

Following the sample reclassification scheme defined in Rajabi (2024), 49 initial detailed classes collected during photointerpretation were mapped into eight mutually exclusive target fuel type classes suited for regional machine learning predictions (Table 1).

Class	Description
Tree B E	Broadleaf Evergreen Forest (e.g., <i>Quercus ilex</i> , <i>Quercus suber</i>)

Tree B D	Broadleaf Deciduous Forest (e.g., <i>Quercus pubescens</i> , <i>Castanea sativa</i>)
Tree N E	Needleleaf Evergreen Forest (e.g., <i>Pinus pinea</i> , <i>Pinus halepensis</i>)
Shrubs	Mediterranean Maquis and Garrigue (<i>Arbutus unedo</i> , <i>Erica arborea</i> , <i>Pistacia lentiscus</i> , <i>Cistus</i> spp.)
Grass	Natural annual grasslands and unmanaged herbaceous pastures
Crops Herbaceous	Annual agricultural cropland, cereal fields, and herbaceous cultivated land
Crops Woody	Permanent agricultural woody crops, olive groves, and vineyards
Urban	Built-up areas, artificial impervious surfaces, and transport infrastructure

Table 1. Fire fuel classes description.

Mixed tree canopy classes (Tree|N|D, Tree|Mixed) and peatland classes were excluded due, the latter being not present in the study site.

3. Materials and methods

The methodological framework developed in this study integrates satellite pre-processing, training sample collection, multi-sensor features extraction, machine learning classification, and spatial performance evaluation. The workflow follows the operational protocols designed within the European H2020 FirEurisk project.

3.1 Satellite data

Sentinel-2 Level-2A Bottom-of-Atmosphere (BOA) surface reflectance imagery were collected over the 32TMK for the observation period 2019. Cloud masking was performed applying threshold 0.5 to the corresponding acquisitions available in the GEE S2 cloud probability dataset. From the cloud-masked surface reflectance time series, monthly synthesis of vegetation indices (VIs) was computed at 10 m spatial resolution (namely ReNDVI, NDMI, kNDVI). In addition, daily Sentinel-2 Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) time series were collected from Copernicus Land Monitoring Service catalogue and used to generate monthly synthesis.

To extract dynamic phenological descriptors, time series harmonic regression was executed on the monthly-aggregated VI series using linear least-squares regression. For each VI time series, harmonic terms representing the baseline mean, annual seasonal amplitude, and seasonal phase timing were computed. kNDVI was not used for harmonic regression, but for calculating annual and seasonal time-series synthesis.

PlanetScope images were also collected for the year 2019; a total of 92 scenes were downloaded among the available acquisitions, covering all four seasons of year 2019 with cloud cover less than 20%. Each PlanetScope scene covers an area of approximately 200 km².

Daily multispectral imagery acquired by DOVE sensor onboard the PlanetScope satellites constellation consists of Bottom Of Atmosphere (BOA) reflectance at 3 m spatial resolution featuring Visible (Blue, Green, Red) and NIR spectral bands. PlanetScope data were processed following the procedure described in Filipponi et al. (2024). Single PlanetScope scenes were mosaicked and spatially clipped to the study area extent,

masked from bad pixels (cloud, cloud shadow, snow, anomalous reflectance, topographic shadow) and a radiometric terrain correction was applied. Since a topographic shadow area mask is not available in PlanetScope *Usable Data Mask*, it was calculated using module *r.sun* available in *GRASS GIS* software. Later, seasonal synthesis metrics were generated for further data processing.

3.2 Training Data Collection

Training and validation samples were collected using a custom open-source Python web application developed for the FirEurisk project by institutes of the National Research Council of Italy (CNR-IGAG, CNR-IREA, CNR-IBE). The app generates Regions Of Interest (ROIs, 100 m × 100 m) aligned with the Sentinel-2 10 m grid for the collection of samples based on a stratified random sampling scheme (based on CORINE Land Cover Plus CLC+ classes) thus ensuring balanced representation of land cover types; for each ROI, it supports pixel-level labelling (10 m × 10 m) by photointerpretation.

Domain experts photointerpreted each ROI using a multi-layer web interface providing: i) high-resolution regional orthophotos of Sardinia (0.2 m spatial resolution, 2019); ii) Google Satellite high-resolution imagery; iii) Google Street View street-level panoramas (critical for verifying tree leaf type — broadleaf vs. needleleaf — and distinguishing shrubs from grass); iv) plots of time series of Sentinel-2 vegetation indices (NDVI, NDMI, SAVI, EVI) to distinguish vegetation with different phenology. The photointerpreters label individual 10 m pixels within each ROI. Pixels where a single fuel class exceeded 75% areal cover were designated as pure pixels. Mixed pixels (containing two classes each between 25% and 75%) were excluded from model training to prevent boundary noise.

A total of 245 ROI samples were collected across tile 32TMK, yielding thousands of pure labelled training pixels across the eight fuel classes (Table 1).

3.3 Static features

To complement optical remote sensing features with structural and topographic drivers of vegetation distribution, static environmental layers at 10 m resolution were collected to generate the following static features set: elevation (m a.s.l.), extracted from the Sardinia Digital Terrain Model (DTM); slope (degrees), computed from DTM; aspect (degrees), derived from DTM, capturing terrain orientation and solar irradiance exposure; Canopy Height Model (m), a high-resolution global canopy height model derived from ETH GEDI-LiDAR and Sentinel-2 (Lang et al., 2023); Above Ground Biomass (t/ha), generated and distributed in the framework of ESA-CCI (Santoro et al., 2024); Agriculture thematic layer, collected from regional thematic maps catalogue, including classes non-agricultural, mixed cropland, woody crops, herbaceous crops.

3.4 Features set

To rigorously evaluate the incremental value of multi-sensor fusion, a total of 114 features were engineered and structured into three distinct experimental feature sets. The features belong to three main groups:

1. Sentinel-2 (36 Features), consisting of kNDVI seasonal synthesis (20) and harmonic components (16), including FAPAR (Mean, Amplitude, Phase), ReNDVI (Mean, Amplitude, Phase), NDMI (Mean, Amplitude, Phase).

2. PlanetScope (72 Features), consisting of kNDVI seasonal composites (4), zonal statistics (20) (kNDVI 10 m mean, standard deviation, CV across seasons), GLCM Textural Features (56) (14 GLCM texture metrics using a 9x9 pixel kernel over 4 seasonal kNDVI composites).
3. Static (6 Features): elevation, slope, aspect, canopy height, above ground biomass, agriculture thematic layer.

The three experimental sets of features are: i) Sentinel-2 + static (42 features); ii) PlanetScope + static (78 features); iii) Sentinel-2 + PlanetScope + static (114 features).

3.5 Machine Learning modeling

Classification modeling was implemented in Python using the XGBoost (eXtreme Gradient Boosting) ensemble decision tree algorithm. XGBoost was selected for its robust performance with high-dimensional feature spaces, native handling of feature interactions, computational efficiency, and the fact that multicollinearity does not cause fluctuations in predictions (which continue to capture the underlying signal).

To prevent spatial autocorrelation from artificially inflating accuracy metrics, a common pitfall in remote sensing pixel level classification, where pixels from the same ROI patch appear in both training and testing sets, the dataset was partitioned using a strict spatial 80/20 train/test split at the ROI patch level. All pixels belonging to a single ROI patch were assigned exclusively to either the training set (80%, ~196 ROIs) or the test set (20%, ~49 ROIs). In addition, hyperparameters were tuned to reach an optimal set (Table 2).

Model performance was evaluated on the independent test set using standard validation metrics: i) Overall Accuracy (OA), the proportion of correctly classified test pixels relative to total test samples, which was evaluated for both training and testing to monitor model overfitting; ii) normalized confusion matrices, displaying Producer's Accuracy (Recall) along the main diagonal and inter-class error rates across off-diagonal cells; iii) class-specific F1-Score, i.e. harmonic mean of Precision and Recall for each individual class.

Hyperparameter	Value
booster	gbtree
gamma	1
max_depth	3
min_child_weight	300
tree_method	hist
n_estimators	50
colsample_bylevel	0.5
colsample_bynode	0.5
colsample_bytree	1
eta	0.5
sampling_method	uniform
subsample	0.5
objective	multi:softprob
num_class	8
eval_metric	merror
random_state	42

Table 2. XGboost hyperparameters set.

In addition, the feature importance, the gain-based importance scores derived from XGBoost, quantifying the relative contribution of individual features to tree split decisions, was calculated to identify the most important features.

4. Results and Discussion

4.1 Overall classification performance

The overall classification results reveal several key insights regarding multi-sensor integration. All three configurations achieved comparable test overall accuracies in the range 74.0–74.7%, aligning closely with baseline Sentinel-2 classification benchmarks established in Mediterranean regional studies. Replacing Sentinel-2 features with high-resolution PlanetScope features (PlanetScope + static) yielded a slight increase in overall test accuracy (+0.61% over Sentinel-2 + static), rising from 74.05% to 74.66%. Combining all 114 features (Sentinel-2 + PlanetScope + static) produced a test accuracy of 74.46%, performing essentially on par with PlanetScope alone (+0.41% over Sentinel-2 alone). Training accuracy increased progressively as feature dimensionality expanded, rising from 81.78% (S2) to 84.12% (PS) and 84.48% (S2+PS), indicating a moderate increase in model complexity and feature redundancy when combining 114 features.

While overall accuracy metrics suggest comparable performance across models, examining class-specific F1-scores and confusion matrices reveals dramatic underlying differences in how optical sensors discriminate individual fuel types.

4.2 Fuel types classification accuracy

Normalized confusion matrices for the three experimental features sets are shown in Figure 1 and F1 score achieved by each fuel class is shown in Figure 2, expressed in the range 0-1. The most significant advance achieved by incorporating PlanetScope acquisitions is a substantial improvement in identifying evergreen tree canopy classes.

In the baseline Sentinel-2 model set, broadleaf evergreen trees (Tree|B|E) (*Quercus ilex*, *Quercus suber*) exhibited low separability, yielding an F1-score of only 0.49 and a Producer's Accuracy of 0.46.

Adding PlanetScope features increased the F1-score to 0.58 in the combined model and 0.66 in the PlanetScope-only model, with Producer's Accuracy rising to 0.58. The F1-score for coniferous stands of class needleleaf evergreen (Tree|N|E) (*Pinus pinea*, *Pinus halepensis*) increased markedly from 0.77 (Sentinel-2) to 0.84 (combined and PlanetScope models), with Producer's Accuracy increasing from 0.66 to 0.75.

This performance boost occurs because evergreen tree canopies maintain relatively flat, non-dynamic spectral vegetation index curves throughout the year, offering limited seasonal phenological amplitude for Sentinel-2 multi-temporal harmonic fitting. However, evergreen forest canopies possess highly distinct spatial textures and canopy roughness patterns. The 3 m spatial resolution of PlanetScope imagery captures fine-scale shadow casting, crown-gap variations, and inter-canopy spatial heterogeneity that are smoothed out within 10 m Sentinel-2 pixels. GLCM textural parameters computed over 3 m PlanetScope kNDVI composites effectively isolate these micro-structural canopy signatures.

Despite this improvement, substantial confusion among fuel classes remains. In the combined model (PlanetScope + Sentinel-2), 38% of broadleaf evergreen tree pixels were erroneously classified as shrubs. In Mediterranean ecosystems, broadleaf evergreen oak forests and tall maquis shrublands share nearly identical sclerophyllous leaf optical properties (*Quercus ilex* vs. *Arbutus unedo* / *Pistacia lentiscus*), making spectral separation impossible without 3D canopy height data or ultra-high-resolution spatial texture.

Conversely, evaluating the grass fuel class highlights a limitation of PlanetScope imagery: when relying strictly on

PlanetScope features set (PlanetScope + static), the F1-score for grass decreased to 0.20 (from 0.41 with Sentinel-2 + static).

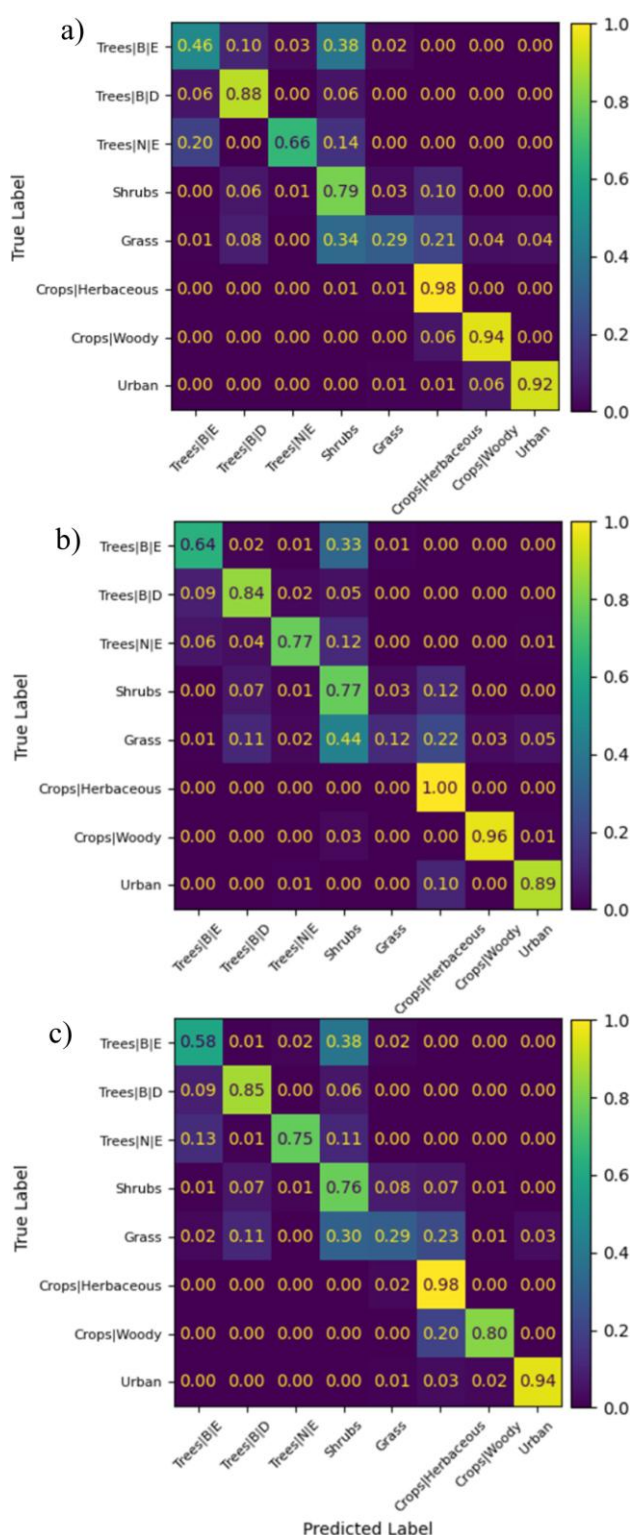


Figure 1. Normalized confusion matrix for the three experimental features sets. a) Sentinel-2 + static. b) PlanetScope + static. c) Sentinel-2 + PlanetScope + static.

In the normalized confusion matrix for the combined model, Producer's Accuracy for grass was only 0.29, with 30% of grass

pixels misclassified as shrubs and 23% misclassified as Crops|Herbaceous. This severe performance drop stems directly from the radiometric band configuration of PlanetScope sensors, which lack Short-Wave Infrared (SWIR) bands. In Mediterranean ecosystems, annual grasslands and herbaceous crops undergo intense summer senescence, drying out completely by July. SWIR reflectance is highly sensitive to leaf equivalent water thickness and dry ligno-cellulose absorption features, allowing Sentinel-2 to discriminate dry natural pasture residue from cultivated crop stubble and bare soil. Without SWIR bands, PlanetScope Visible-NIR reflectance bands cannot separate dry senescent grass from herbaceous cropland, causing severe class confusion.

Agricultural croplands represent the most complex and dynamic landscape component within the study site. Herbaceous crops (Crops|Herbaceous) achieved high individual Producer's Accuracy (0.98) due to distinct seasonal plowing, planting, and green-up cycles captured by multi-temporal harmonic VIs. Permanent woody crops (Crops|Woody, e.g., olive groves, vineyards) achieved F1-scores between 0.86 and 0.95. However, spatial error analysis demonstrates that agricultural fields remain the primary source of spatial disagreement between classification models. Variable irrigation schedules, crop rotation schemes, field-edge vegetation, and inter-annual fallow field dynamics introduce high spatial-temporal heterogeneity that challenges automated pixel-based classifiers.

4.3 Features importance

Analysing the top-ranked features reveals a remarkable synergistic interplay between high-resolution spatial texture and multi-spectral temporal dynamics (Table 3). The most important feature is GLCM_PS_kNDVI_2019_SON_Entr (PlanetScope September to November kNDVI GLCM Entropy), emerged as the single most influential predictor overall by receiving an importance score of 0.091. GLCM Entropy measures the randomness and spatial structural disorder of 3 m kNDVI values within a 9×9 pixels window. During autumn season (September to November), Mediterranean vegetation transitions following first rainfalls: pastures re-green rapidly, deciduous trees drop leaves, and evergreen canopies remain structurally stable. High spatial entropy highlights the presence of complex, multi-layered forest canopies and fragmented maquis ecotones. Second most important feature was ReNDVI_phase_1 (Sentinel-2 Red-Edge NDVI annual harmonic phase component, importance score 0.074). Red-Edge NDVI phase captures the exact day of the peak of annual greenness, providing an indispensable diagnostic feature separating broadleaf deciduous tree (spring peak) from broadleaf evergreen trees and pastures. Features describing autumn minimum vegetation vigour (namely S2_kNDVI_2019_SON_min, score 0.046; S2_kNDVI_2019_SON_mean, score 0.044) ranked 3rd and 4th. Late-summer and autumn minimum kNDVI values reflect residual vegetation moisture and greenness at the peak of seasonal drought, serving as a powerful discriminant between evergreen woody species (which retain green foliage) and senescent herbaceous cover. Canopy height model obtained a score of 0.041, confirming that 3D structural parameters provide crucial upper boundary limits separating tree categories from low-growing shrublands and herbaceous cover.

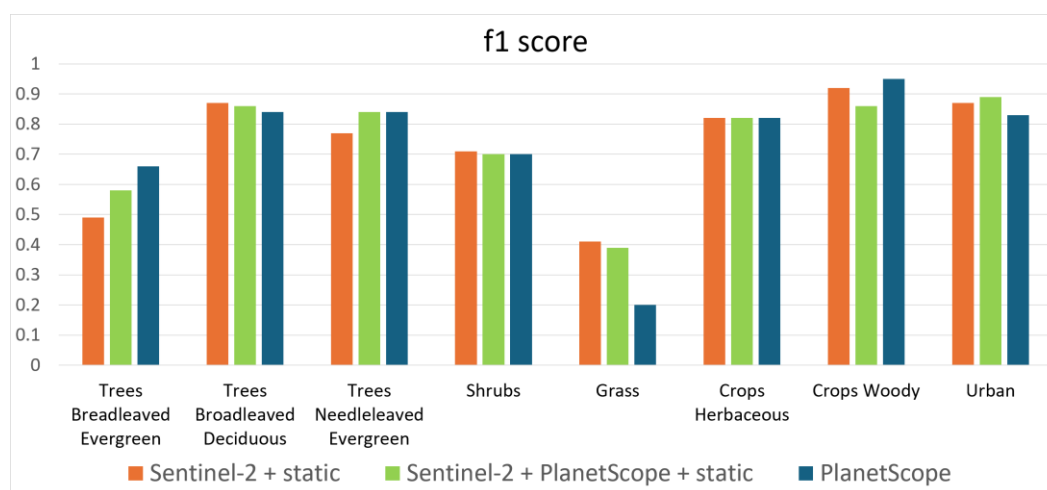


Figure 2. F1 score achieved by each fire fuel class for the three features sets.

PlanetScope seasonal coefficient of variation metrics describing winter and spring texture and variability (PS_kNDVI_2019_DJF_cv, score 0.040; PS_kNDVI_2019_MAM_cv, score 0.032) ranked among the top 10 features, capturing fine-scale seasonal changes in canopy openness.

Rank	Feature	Domain	Set	Score
1	GLCM_PS_kNDVI_2019_SON_Entropy	Planet Scope	Texture	0.091
2	ReNDVI_phase_1	Sentinel-2	Harmonic	0.074
3	S2_kNDVI_2019_SON_min	Sentinel-2	Phenology	0.046
4	S2_kNDVI_2019_SON_mean	Sentinel-2	Phenology	0.044
5	canopy_height	Static	LiDAR	0.041
6	PS_kNDVI_2019_DJF_cv	Planet Scope	Zonal	0.040
7	ReNDVI_mean	Sentinel-2	Harmonic	0.040
8	PS_kNDVI_2019_SON_mean	Planet Scope	Zonal	0.033
9	S2_kNDVI_2019_min	Sentinel-2	Phenology	0.033
10	PS_kNDVI_2019_MAM_cv	Planet Scope	Zonal	0.032

Table 3. Top 10 feature importance ranking (XGboost).

Acronyms: GLCM, Gray-Level Co-occurrence Matrix; PS, PlanetScope; S2, Sentinel-2; kNDVI, kernel Normalized Difference Vegetation Index; ReNDVI, RedEdge Normalized Difference Vegetation Index; min, minimum; cv, coefficient of variation; Entr, entropy; DJF, December January February (winter season); MAM, March April May (spring season); SON, September October November (autumn season).

4.4 Regional fire fuel map

Applying the trained XGBoost model (114 features) in the pilot site produced a continuous, high-resolution (10 m grid) regional fuel type map covering western Sardinia (Figure 3). Visual inspection confirms high spatial consistency with regional orthophotos and vegetation inventories. Dense broadleaf

evergreen forest stands (Tree|B|E) are correctly mapped across interior mountain ridges (e.g., Montiferru, Monte Arci), and mixed shrubland/maquis complexes (Shrubs) form continuous transition belts surrounding forested massifs. Agricultural croplands (Crops|Herbaceous, Crops|Woody) and herbaceous pastures (Grass) cleanly delineate the flat plains of Campidano. When compared against coarse-resolution products, such as the 1 km European FirEUrisk Fuel Map, the 10 m multi-sensor map offers unprecedented spatial detail, capturing narrow riparian woodland corridors, fragmented agricultural woodlots, and fine-scale wildland-urban interface fuel patterns critical for local fire propagation modeling and emergency response planning.

5. Conclusions

This study demonstrates the scientific and operational advances achieved by synergistically integrating Sentinel-2 multispectral time series and high-resolution textural metrics from PlanetScope images for mapping fuel type at regional scale in complex Mediterranean environments. Building directly upon baseline Sentinel-2 classification research in Sardinia, this study establishes that combining fine spatial texture with dense multi-spectral temporal dynamics significantly enhances fuel classification metrics.

The core conclusions and takeaways of this research are summarized below. Spatial texture enhances tree canopy mapping: fusing PlanetScope 3 m acquisitions into the feature matrix markedly improved classification performance for evergreen forest canopies. F1-scores increased from 0.49 to 0.58–0.66 for broadleaf evergreen trees (*Quercus ilex*, *Quercus suber*) and from 0.77 to 0.84 for needleleaf evergreen trees (*Pinus* spp.). High-resolution spatial texture captured by PlanetScope GLCM kNDVI Entropy (GLCM_PS_kNDVI_2019_SON_Entropy) emerged as the single most influential predictor variable overall (importance score 0.091).

PlanetScope acquisitions alone are insufficient for complete Mediterranean fuel mapping, making the complementary nature of Sentinel-2 spectral bands essential. Due to the absence of Short-Wave Infrared (SWIR) bands on PlanetScope sensors, models relying strictly on PlanetScope performed poorly on the grass class (F1-score 0.20), failing to distinguish dry senescent summer pastures from herbaceous crop residue. Sentinel-2 SWIR and Red-Edge spectral bands remain indispensable for capturing vegetation water content, leaf senescence, and phenological phase timing. The combination of PlanetScope 3 m spatial texture and Sentinel-2 10 m multi-spectral temporal

harmonics provides a highly robust, dual-scale framework for operational wildfire hazard modeling across heterogeneous Mediterranean landscapes.

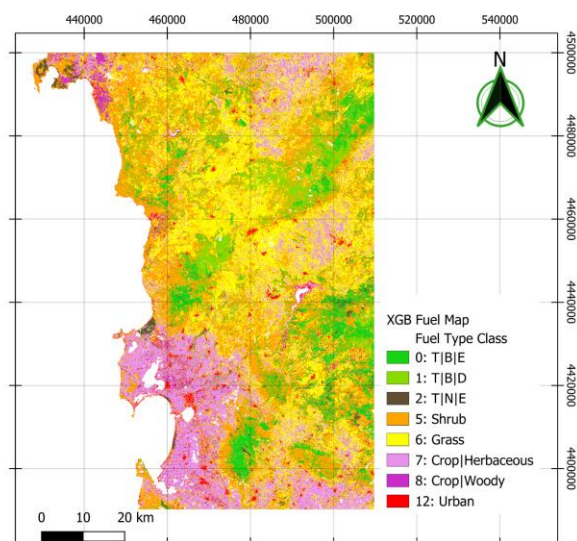


Figure 3. Fire fuel map generated for the study area.

Despite these advances, key methodological challenges remain to be addressed in future work. Substantial spectral-textural overlap persists between broadleaf evergreen oak trees and tall, dense maquis shrublands (38% confusion). Incorporating active 3D canopy penetration datasets, such as airborne LiDAR height profiles or spaceborne waveform metrics, could resolve understory canopy layers and vertical fuel continuity (Domingo et al., 2020).

Future research should expand training sample collection across broader climatic, soil, and vegetation gradients to support spatial-temporal extrapolation across the entire island of Sardinia and adjacent regions in the Mediterranean basin.

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