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Assessing the distribution and condition of wooden roofs in Slovenia through citizen science and complementary analytical methods

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Abstract: Wooden roofs are an important component of Slovenia's and Alpine architectural heritage, but conserving them requires information on distribution, moisture performance, and maintenance practices. This study combined citizen science, remote mapping, laboratory testing, outdoor moisture monitoring, and elemental characterisation. A citizen science inventory documented 130 structures, concentrated in Alpine and pre-Alpine regions; pastoral buildings accounted for 40.8% of records. Remote mapping, seems more effective and identified about 280 candidate wooden-roof features in the Velika Planina area, providing complementary coverage but requiring verification of potential misclassifications. Roofs were traditionally made of split shingles, which are nowadays replaced by sawn ones. To compare the moisture performance of these two materials, laboratory immersion and spraying tests showed that split shingles wetted more than sawn spruce shingles. Outdoor monitoring yielded similar outcomes, without a consistent advantage across elevated-moisture thresholds. Unfortunately, shingles are frequently treated with waste lubricant oil. Thus, portable X-ray fluorescence measurements on 30 cabins, supported by microscopy and micro-XRF, revealed surface deposits consistent with reported waste lubricating oil treatments. Principal component analysis differentiated treatment groups, supporting its application for exploratory screening. Iron and sulfur accumulated predominantly near shingle surfaces. Deterioration is accompanied with moisture content increase. These findings support integrated inventories, moisture-conscious roof detailing, and environmentally appropriate maintenance, while identifying waste-oil application as a potential contamination source requiring direct environmental assessment to quantify releases and impacts.

Keywords: Wooden shingles; Citizen science; Moisture performance; X-ray fluorescence; Waste lubricating oil

Introduction

Wooden roofs are an enduring component of European architectural heritage, with archaeological evidence of shingles from the Bronze Age Hallstatt [1]. In seventeenth-century Slovenia, wooden roofing distinguished churches, castles and other important buildings, whereas many farmhouses were thatched. The subsequent shift to tiles and industrial roofing materials reduced their prevalence, but wooden roofs remained characteristic of Alpine settlements, including Trenta, southern Carinthia, and Velika Planina. Their significance extends beyond the roof covering to local wood selection, craftsmanship and the transmission of shingle-making knowledge [2,3].

Recent research has shifted from documenting these traditions to understanding the moisture and temperature conditions that govern shingle roof performance. Ventilation, orientation, overlaps, and shingle geometry influence wetting and drying; consequently, ambient weather alone cannot adequately describe exposure to decay. Kain and coworkers [1] showed that ventilation benefits depend on roof configuration, while monitoring at the Golobar cable yarding showed that grooved and wax-treated spruce shingles performed better in moisture terms [2]. Long-term performance is also documented for grooved decking in Australia [4]. Namely, lower moisture content indicates reduced decay risk and provides indirect evidence of extended service life [5]. The ageing of traditional tar coatings further underscores the importance of maintenance and exposure-specific assessment [6].

Climate change increases the urgency of this research because fungal decay depends jointly on temperature, available moisture and exposure duration [7–9]. Warmer conditions can prolong periods favourable for fungal activity when wood remains wet, whereas enhanced drying may locally reduce the risk. In Slovenia, historical meteorological analyses revealed increasing Scheffer climate indices at most investigated sites, with the greatest increase in Alpine valley Rateče, indicating rising climatic decay potential in Alpine regions rather than directly measured roof deterioration [10]. Similar trends are reported or forecast in other European countries [11]. Roofs designed under earlier climatic conditions therefore require reassessment

based on their actual material climate. Their high initial cost, reflecting selected timber and labour-intensive manufacture and installation, makes premature replacement particularly consequential. Nevertheless, conservation requirements may still require wooden coverings to preserve architectural authenticity and landscape character.

Ecologically, wooden roofs offer a renewable material option, store biogenic carbon temporarily, and support local sourcing and repair by replacing individual shingles. These advantages depend on responsible forestry, transport, maintenance and service life; frequent replacement can erode the expected benefits. Their limitations include susceptibility to fungi, weathering, dimensional movement, combustibility, and maintenance demands [12]. Protection also introduces environmental trade-offs: laboratory leaching tests identified releases of copper, boron and nitrogen compounds from treated wooden shingles, demonstrating that biological resistance and runoff quality must be considered together [13]. A natural material designation alone is therefore insufficient evidence of environmental superiority.

Shingle preparation is central to reconciling durability, cost and conservation. Traditional practice favours carefully selected, straight-grained timber without defects, with spruce, larch and silver fir being commonly used according to regional availability. Radial splitting generally follows the grain, whereas sawing cuts across fibres and allows for use of different timber qualities and geometries; therefore, the goal was to evaluate the preparation method alongside species, grain orientation, thickness, and installation details [14]. For Slovenia, when considering the service life of wooden shingles, special attention should be given to unsuitable surface treatments that are commonly applied to wooden shingles. In particular, the use of potentially ineffective surface treatment agents such as waste lubricating oils. The efficacy of these materials, without considering the penetration depth and retention, cannot be deemed adequate. Furthermore, they can impede drying as well as present an environmental hazard due to their composition and leaching from the treated surfaces due to UV and rain exposure. [15].

In order to study the distribution of wooden roofs, the citizen science approach was used. The authors asked citizens to help map wooden roofs in Slovenia. Using this participatory approach, the key region with the highest presence of wooden roofs was identified: Velika Planina. In addition to the participatory approach, the remote sensing

approach was used as well. From the orthophoto images of Velika Planina recorded with various techniques, the wooden roofs were identified. The approach was confirmed with an on-site visit, where the presence of inappropriate treatment techniques and installation details were studied.

Materials and methods

Roof distribution in Slovenia – case study of citizen science

A citizen science approach was used to document wooden roofing in Slovenia through a structured online questionnaire entitled "*Lesene strehe"* (Wooden roofs), implemented in Microsoft Forms. The questionnaire asked participants to report the location and characteristics of wooden-roofed structures and assess their roof condition. Citizen contributions combined local knowledge with observations of accessible structures, providing geographically referenced records for an exploratory inventory.

Data collection took place between April 2025 and June 2026. Participants were recruited through direct email invitations and social media. Participation was voluntary and open to anyone interested. The inventory was based on submitted observations rather than a predefined probability sample. Accordingly, its spatial coverage depended on participant access, awareness, and willingness to contribute. The records were therefore treated as observations of documented structures rather than as a statistically representative sample of all wooden roofs in Slovenia.

Questionnaire structure and recorded variables

The questionnaire included 11 questions covering location, building characteristics, roof condition, shingle manufacturing method, surface treatment, and respondent demographics. Four questions were mandatory: administrative region, address or geographic coordinates, building type, and primary wall material.

The questionnaire did not provide separate scoring criteria for individual defects; consequently, the ratings were not interpreted as measurements of fungal decay, mechanical strength, or structural safety. The shingle manufacturing method was recorded as split, sawn, or unknown. Participants were also asked whether the roof had received a surface treatment. Response options included no treatment, waste motor oil, a wood preservative, a natural oil such as linseed oil, a varnish, wood stain

or another wood coating, and an open response. These entries represented reported treatment histories and were not treated as chemically verified identifications. Participants could additionally upload photographs of the documented structures.

The supplied analytical spreadsheet contained 130 original records. Original entries were retained, and harmonised variables were created for analysis. The inventory was summarised using descriptive statistics. Categorical variables were presented as frequencies and percentages, with the denominator set to the number of eligible records with usable information for the relevant variable. Missing responses were not interpreted as absence of a characteristic, and explicit “unknown” responses were distinguished from missing data.

Roofs in Velika Planina – case study of remote detection

The citizen science inventory identified the Velika Planina area as a location of interest for further investigation of wooden roofing. This area was subsequently selected for remote sensing assessment and a field survey combining roof documentation with portable XRF measurements.

Spatial analyses were performed using the QGIS Desktop 3.40.12 "Bratislava" geographic information system. Data were processed within the national coordinate system D96/TM (EPSG:3794). Digital orthophotos (DOF) served as the raster base (Figure 3), while building outlines were derived from the National Topographic Model, provided by the Surveying and Mapping Authority of the Republic of Slovenia [16].

Supervised classification was carried out using the “Dzetsaka” Classification Tool plugin. Representative training areas were manually selected on the orthophotos and assigned to the following classes: wooden roofs, stone or other types of roofs, forest, and grassland. Each class was assigned a unique identification number and label. The classification used the “CatBoost” algorithm, based on the red, green, and blue channel values from the orthophotos.

Multiple orthophoto tiles were combined into a single virtual raster using the "Build Virtual Raster" tool. The classification result was then clipped to the building polygons using the "Clip Raster by Mask Layer" tool, thereby excluding surrounding features such as forests or grasslands from further analysis. The "Zonal Statistics" tool was

used to calculate the dominant classification value for each building polygon. Finally, the results were visualised; buildings identified as having wooden roofs are displayed in yellow on the final map (Figure 4).

Moisture experiment design

The moisture performance experiment compared spruce shingles prepared using different manufacturing methods and underside configurations. The experimental groups comprised untreated sawn shingles, sawn shingles with longitudinal underside grooves, and untreated split shingles. Laboratory water uptake tests and outdoor moisture monitoring were used to characterise their wetting and drying behaviour.

One question about wooden roofs concerns the performance of split versus sawn wooden shingles. Norway spruce (*Picea abies*) shingles were used to investigate the effects of shingle manufacturing method on water uptake and outdoor moisture dynamics. Sawn shingles were manufactured to dimensions of 1000 mm × 150 mm × 15 mm. Their exposed surfaces remained unplanned after sawing. We used split spruce shingles as the comparison to traditional manufacture and selected them to match the sawn shingles' dimensions as closely as possible.

Smaller specimens measuring 195 mm × 100 mm were cut from the shingles. Ten specimens were prepared per group, with five allocated to laboratory testing and five to outdoor exposure. Full-sized shingles were reserved for outdoor moisture monitoring.

The wood materials used in this study were purchased or received as donations and were not cultivated specifically for the research. All wood originated from sustainably managed forests in Slovenia, and its procurement was not associated with illegal logging or deforestation.

Laboratory water uptake

Before immersion testing, specimens were conditioned at approximately 20 °C and 65% relative humidity and weighed. They were placed between plastic meshes in steel containers, allowing water access to their lower surfaces while preventing flotation.

Specimens underwent successive immersion periods of 1 minute, 10 minutes, and 1 hour in distilled water. Following each period, excess surface water was removed with a cloth and specimens were weighed immediately. Fresh water was used for each immersion period to limit interference from leached treatment constituents.

Rainfall exposure was simulated in a chamber equipped with overhead spray nozzles distributed across the specimen area. Before testing, specimens were oven-dried at 103 ± 2 °C for 24 hours, cooled over silica gel for 15 minutes, and weighed to determine dry mass. After 24 hours at room conditions, specimens were reweighed and exposed to spraying for 10 minutes at an approximate total water flow of 10 L min^{-1}. Surface water was removed before weighing. A second, one-hour exposure followed after 14 days of equilibration at room conditions.

Outdoor moisture monitoring

Shingles were mounted on racks inclined at 45°, spaced to allow ventilation. Their ends were sheltered to approximate protection provided by overlapping roofing elements. Wood moisture content was monitored using Scanntronik equipment based on electrical resistance measurements. A pair of insulated stainless-steel screw electrodes was installed in each shingle, with a spacing of 32 mm. The system automatically recorded electrical resistance and wood temperature at 12-hour intervals, and moisture content was calculated from these measurements. Monitoring took place between May 2020 and April 2025. In total, 3164 measurements were performed per material during this period. A gap exists due to technical issues. Moisture dynamics were characterised using descriptive statistics and proportions of measurements exceeding 20%, 25%, and 30% wood moisture content.

Elemental characterisation of wooden roofs and surface treatments of wooden roofs in Velika Planina

We conducted a field survey of 30 cabins in the Velika Planina area to investigate elemental variation among wooden roofs with different reported surface treatments. Portable XRF measurements were complemented by laboratory XRF, microscopy, and micro-XRF examination of selected shingles. Treatment information was retained as contextual metadata for interpreting elemental profiles.

Field survey and portable XRF measurements

The elemental composition of wooden roof was investigated on 30 cabins in the Velika Planina area, Slovenia. Each cabin received a unique identifier linking its geographical location, roof characteristics, and analytical measurements. Field documentation included shingle manufacturing method (split or sawn), roof condition, and reported surface treatment. Treatment categories distinguished untreated roofs from roofs treated with oil or varnish. These classifications provided contextual information for comparing elemental profiles among buildings.

We performed in situ X-ray fluorescence measurements using an Olympus Vanta portable XRF analyser. The sampling protocol included three measurements per cabin, for a total of 90 planned measurement positions. Measurements characterised local variation within roofs while allowing comparisons among cabins. The instrument recorded X-Ray fluorescence spectra and calculated elemental concentrations (parts per million), along with analytical uncertainties and non-detection information. The supplied measurement reports predominantly indicated acquisition times of 50 seconds. Instrument operating mode, excitation settings, measurement geometry, and calibration procedures were standard as typical for assessment of soil.

Data preparation and principal component analysis

Spectral and elemental data were organised by measurement identifier and cabin. The concentration spreadsheet contained 88 records representing all 30 cabins; consequently, the final analytical dataset was distinguished from the planned sampling design. Two measurements were excluded due to technical issues during measurements.

We performed principal component analysis (PCA) in GraphPad Prism to explore variation in XRF profiles and their association with reported roof treatments. Two complementary analyses were configured: one using 752 spectral variables and another using concentrations of 23 elements. Variables were mean centred without scaling to unit variance, as specified in the saved analysis settings. Component retention used the Kaiser criterion, with an eigenvalue threshold of 1. Score plots displayed observations according to treatment category, while cabin identifiers supported interpretation of spectral scores. For elemental analysis, we used loading plots and biplots to examine variable contributions. Non-detects were encoded as zero in the supplied concentration matrix; this encoding was distinguished from confirmed elemental absence.

Laboratory examination of shingles

Sample of selected wooden shingles were collected and additionally examined by bench-top XRF, microscopy, and micro-XRF to complement the field survey. Laboratory XRF measurements were performed using Bruker S2 Puma, retaining sample identifiers to connect laboratory observations with field records.

Microscopic examination was conducted using an Olympus OLX1000 instrument. Observations documented shingle morphology and provided a visual framework for interpreting elemental measurements. Spatially resolved elemental analysis on shingle cross-section was performed using a Bruker Tornado micro-XRF instrument. Measurements investigated elemental distributions within selected shingle regions and complemented the larger-area portable XRF observations.

DRIFT spectra were obtained on a PerkinElmer Spectrum Two (PerkinElmer, USA). Two specimens were sampled using SiC abrasive discs, and the spectra were recorded in the range of 4000 – 400 cm^{-1} with a resolution of 4 cm^{-1}. Following acquisition, the spectra were baseline corrected and normalised to the O-H band at 3300 cm^{-1}.

Results and discussion

Roof distribution in Slovenia – case study of citizen science

The citizen science inventory comprised 130 records of structures with wooden roofing. Their distribution was concentrated in northern and northwestern Slovenia, particularly

in the Alpine and pre-Alpine landscapes of the Julian Alps, Gorenjska, and the Kamnik Alps (Figures 1 and 2). A conspicuous cluster occurred around Velika Planina, while further concentrations were visible in the wider Triglav National Park area. Additional records extended towards Koroška and the Savinja region. More scattered observations occurred in central Slovenia, the Dinaric mountains, Dolenjska, and southern Slovenia. Few or no observations were mapped in the northeastern lowlands and southwestern coastal areas. These patterns describe the submitted inventory; the absence of records cannot be interpreted as evidence that wooden roofs are absent from a region.

The concentration of observations in Alpine landscapes was consistent with the strong representation of pastoral structures [17]. Buildings classified as "*planšarija"*, encompassing alpine pastoral huts and dairy buildings, accounted for 53 records (40.8%). Their prominence indicates that wooden roofing remains closely associated with the built heritage of seasonal mountain grazing. This interpretation accords with the documented architecture of Velika Planina, where traditional shepherds huts retain characteristic spruce-shingle roofs. More broadly, pasture architecture in the Julian Alps includes herdsmen's dwellings, stables, hay barns, and cheese dairies, reflecting the infrastructure needed for seasonal livestock management and dairy production [18].

The mapped distribution also suggests an association with hilly, mountainous landscapes with forests and dispersed rural settlements [17]. A plausible explanation is the historical availability of timber, together with local skills in wood processing, allowing for on-site shingle manufacture, and repair. However, material availability should be considered alongside land use and architectural tradition [14]. The cultural landscape of Triglav National Park, for example, combines alpine pastures and dispersed settlements with vernacular buildings constructed using locally available wood and stone. The present inventory did not include a formal comparison with forest cover, terrain, or the total number of buildings [19]. Consequently, the apparent relationship with forested highlands remains an interpretation of the spatial pattern rather than a quantified association. Scattered records outside the Alpine region further show that wooden roofing is not restricted to mountain pastoral settlements.

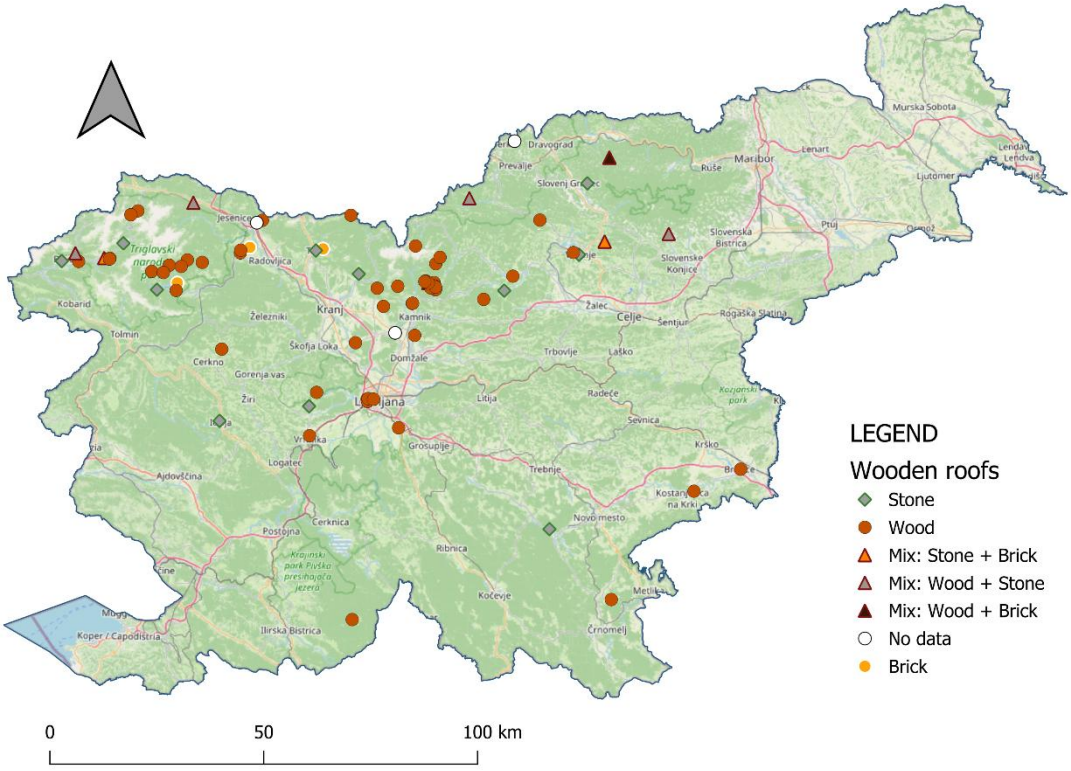

Figure 1: Spatial distribution of structures with wooden roofs recorded through citizen science in Slovenia, classified by primary wall material.

Wood was also the most frequently reported primary wall material, occurring as the sole listed material in 102 records. This represented 78.5% of all observations and 80.3% of the 127 records with wall-material information. A further eight structures combined wood with stone or brick. In total, wood was reported as a wall material in 110 of the 127 documented cases (86.6%). These findings indicate that wooden roofing was predominantly associated with structures also incorporating wood in their walls. Nevertheless, the questionnaire recorded primary wall materials rather than complete construction systems; structures classified as having wooden walls cannot therefore be described unequivocally as entirely wooden.

Seventeen structures with documented wall materials (13.4%) were classified as stone, brick, or combined stone-and-brick construction. Their presence demonstrates that wooden roof coverings also occur on masonry structures. In these cases, shingles represent a roofing choice independent of the primary wall material. The records do not establish that wood was used exclusively for roofing, because roof frames, floors, and other components were not systematically documented. The inventory therefore distinguishes wooden roofing on predominantly wooden structures from wooden

roofing on masonry structures, rather than separating entirely wooden buildings from buildings containing wood only in the roof.

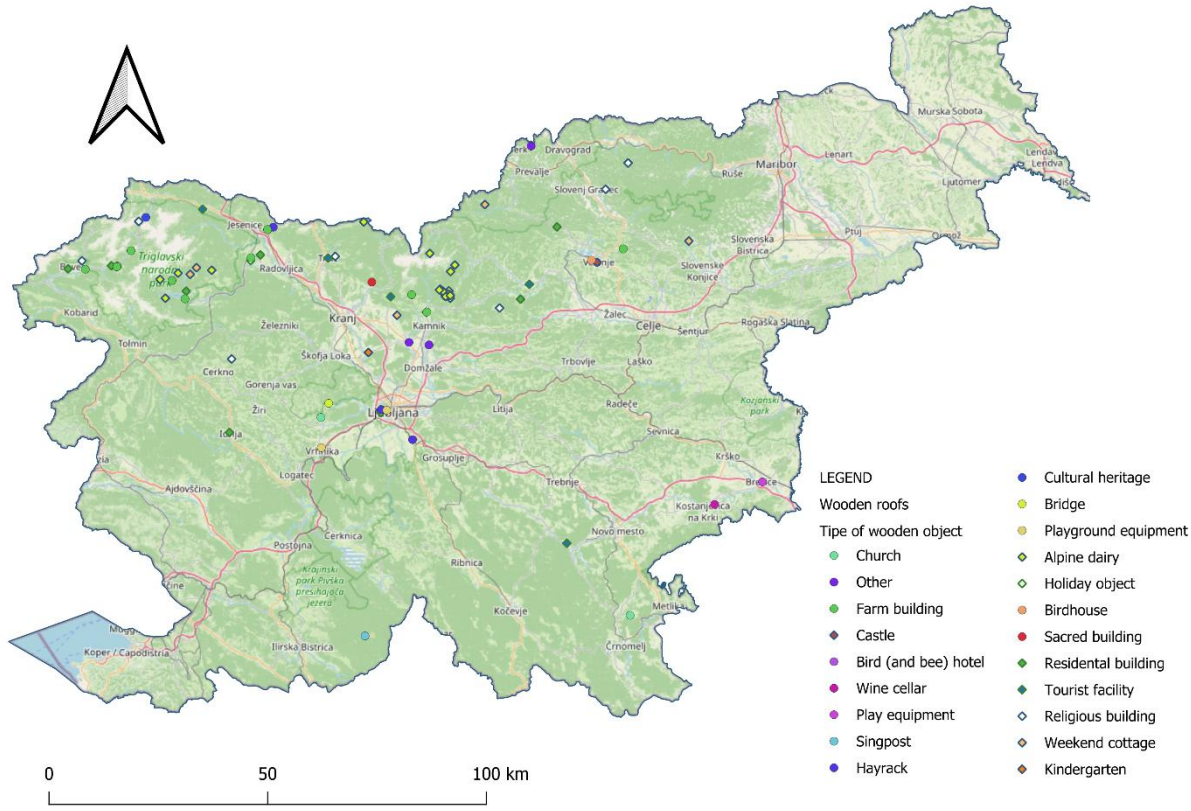

Figure 2: Spatial distribution of structures with wooden roofs recorded through citizen science in Slovenia, classified by structure type.

The recorded functions extended beyond pastoral use. Agricultural outbuildings accounted for 18 records (13.8%), religious structures, including churches, for 16 (12.3%), residential buildings for 10 (7.7%), and holiday or recreational accommodation for another 10 (7.7%). Five structures were explicitly classified as tourist facilities, and three as hayracks. Other observations included heritage structures, a castle, a kindergarten, playground equipment, birdhouses, a bridge, and a signpost. These categories show that wooden roofing serves agricultural, residential, religious, recreational, and small-scale functional purposes. However, recorded structure types do not necessarily establish present-day use, particularly where former pastoral buildings may have acquired recreational or tourism functions.

Roofs in Velika Planina – case study of remote detection

The orthophoto-based inventory identified approximately 280 yellow-marked features interpreted as wooden roofs within the mapped Velika Planina area. It should be noted that more individual buildings may be located within the same pasture cabin, and that even large tables can be interpreted as wooden roofs, since image analysis cannot distinguish between wood used as building material and wood used as tables or decking. Thus, it is somehow understandable that this image-derived estimate substantially exceeded the 130 records collected through citizen science across Slovenia. Although the inventories cover different geographical areas, the comparison shows that a single mountain pasture landscape can contain more potential wooden-roofed structures than voluntary submissions documented nationally. The citizen science inventory should therefore be interpreted as an exploratory record of reported structures rather than a comprehensive census.



Figure 3: Cabins on Velika Planina

The remotely mapped roofs clustered within a landscape of open grassland, scattered trees, and extensive forest. Several concentrations were connected by paths and access tracks, while isolated roofs occurred along pasture margins and within smaller clearings. This pattern is consistent with the spatial organisation of pastoral settlements, where buildings are grouped around grazing areas rather than distributed uniformly across the landscape. The map also reveals that wooden roofing forms a substantial component of the settlement landscape, extending beyond the limited set of cabins examined during the field survey.

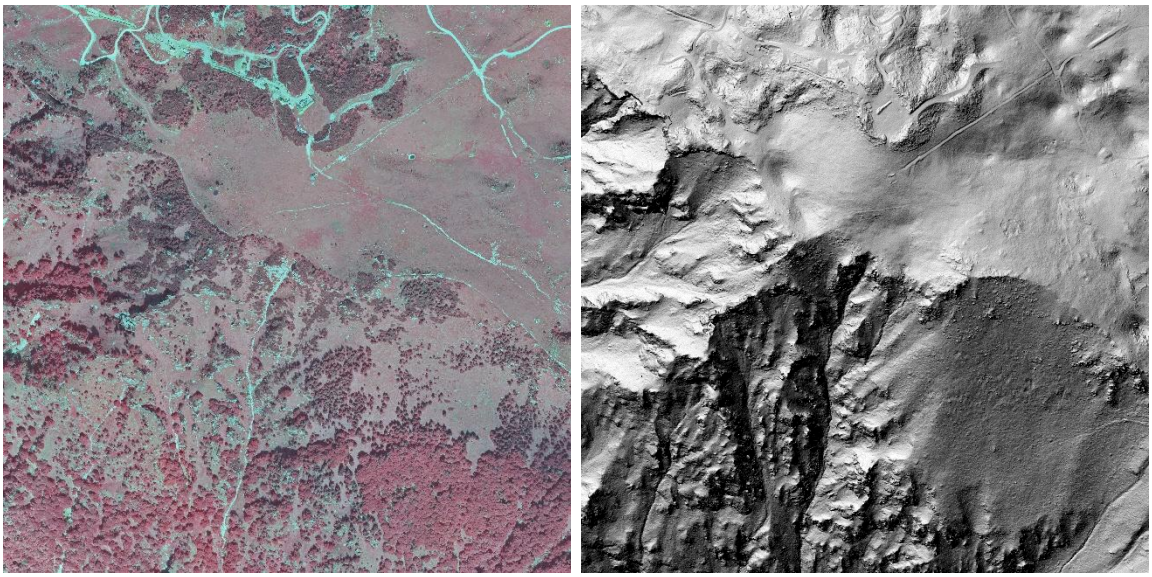

Figure 4: IR (left) and LIDAR (right) image of part of the Velika planina used for the remote sensing of wooden roofs

The difference between the inventories highlights their complementary strengths. Citizen science provided information that cannot be reliably obtained from overhead imagery alone, including structure function, primary wall material, reported surface treatment, and perceived roof condition. However, its coverage depended on participant awareness, accessibility, and willingness to submit observations. As a result, closely spaced cabins may remain undocumented even within well-known settlements. Orthophoto interpretation offered more systematic coverage of the selected area and revealed numerous additional candidate roofs, including structures outside the field survey locations.

Nevertheless, yellow-marked features should not automatically be equated with independently verified wooden-roofed buildings. Closely adjoining roof sections may represent one structure, whereas overlapping markers may conceal separate structures. Shadows, weathered surfaces, and similarities between roofing materials can also complicate identification. The approximate count therefore requires verification against the original mapped polygons or points and, where necessary, field observations. Moreover, the national citizen science total cannot be used to calculate local detection completeness without extracting and matching records within the same geographical boundary.

These findings support an integrated inventory strategy. Citizen science can identify priority areas and supply contextual information, while remote mapping can expand spatial coverage and guide targeted verification. Linking both datasets through geographic coordinates and unique building identifiers would enable duplicate removal, agreement assessment, and identification of unreported structures. For Velika Planina, the combined evidence indicates that wooden roofing is a landscape-scale heritage feature requiring coordinated documentation and maintenance.

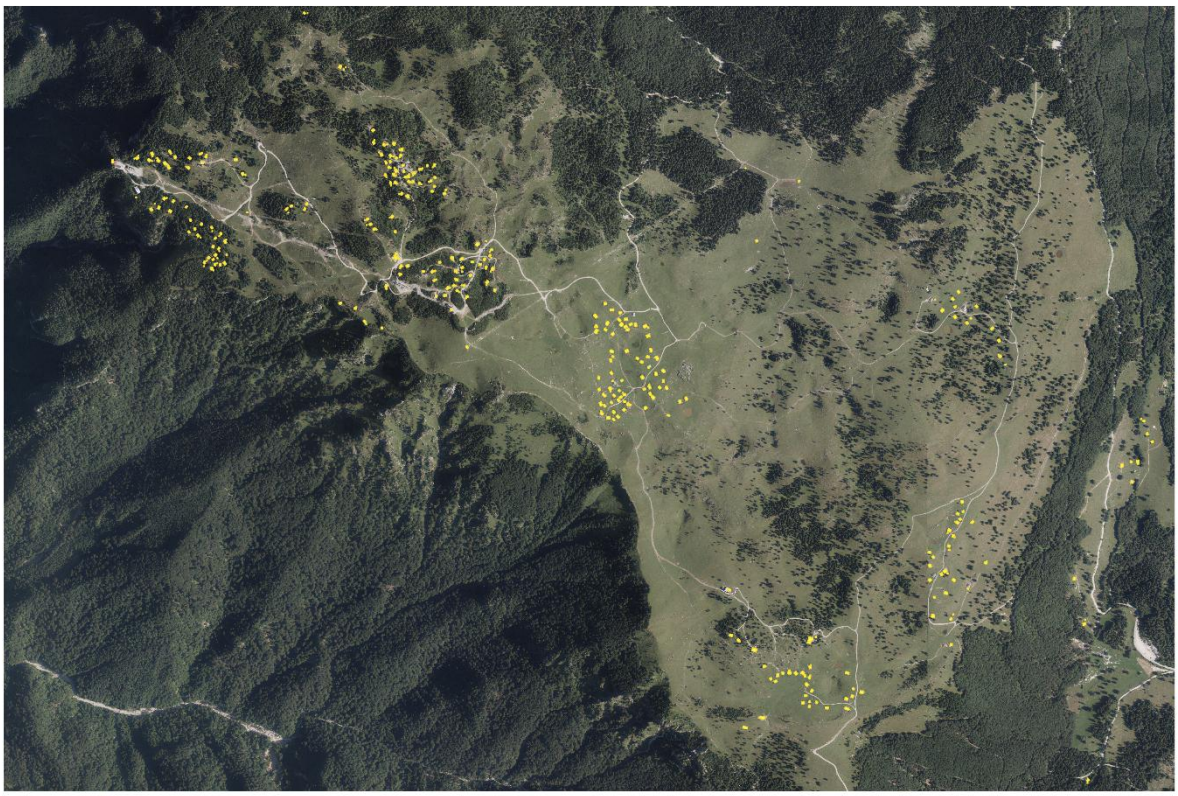

Figure 5: Wooden roofs as determined from the IR images based on remote sensing

Comparison of moisture performance – split or sawn shingles

Both sawn and split shingles exhibited increasing moisture content with increasing immersion duration (Figure 6). After one minute, moisture contents were approximately 15–17%, with relatively small differences between manufacturing methods. Following 10 minutes of immersion, the central values increased to approximately 19% for sawn shingles and 20% for split shingles. After one hour, the corresponding values reached

approximately 23% and 25%. Split shingles therefore showed consistently higher moisture contents, although there is no statistically significant difference ($p > 0.01$).

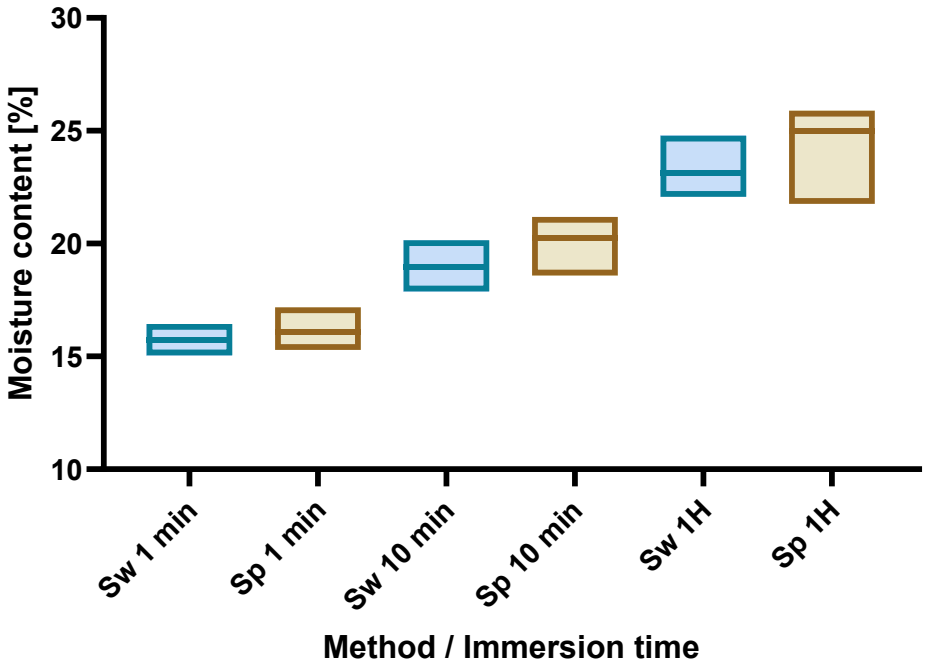

Figure 6: Water uptake of sawn (Sw) and split (Sp) shingles after immersion to water

The simulated rainfall test showed a similar ranking, with greater wetting after longer exposure and consistently higher values for split shingles (Figure 7). After 10 minutes of spraying, the response was about 11% for sawn shingles and 12% for split shingles, increasing to about 19% and 21–22%, respectively, after one hour. The separation between manufacturing methods was more pronounced during prolonged spraying. Thus, splitting to preserve the grain structure did not necessarily reduce wetting under the investigated conditions. The differences between the various shingles were not significant during 10 min spraying but became significant after 1 h ($p < 0.01$).

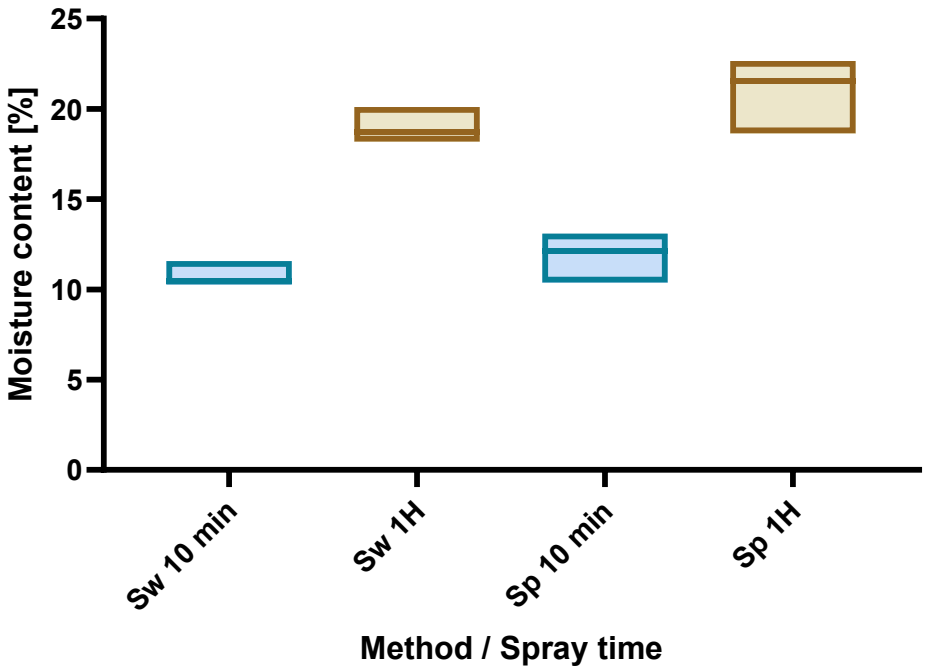

Figure 7: Water uptake of sawn (Sw) and split (Sp) shingles after spraying

Together, the laboratory tests indicate that exposure duration influenced wetting more than manufacturing method. Both methods produced shingles capable of substantial moisture uptake during sustained water exposure. Nevertheless, these experiments characterise wetting behaviour rather than complete moisture performance: resistance to water uptake must be considered alongside subsequent drying. Lower moisture content immediately after wetting indicates longer service life [20].

Table 1. Moisture content indicators for sawn (Sw) and split (Sp) wooden shingles during outdoor exposure, based on 3164 measurements per shingle type.

	Sawn shingle (Sw)	**Split shingle (Sp)**
No of measurements	3164	3164
Average MC (%)	17.5%	18.0%
Median MC (%)	16.9 %	17.7%
% of measurements > MC20%	24.5%	29.6%
% of measurements > MC25%	4.7%	4.5%
% of measurements > MC30%	1.3%	0.9%

The outdoor monitoring series showed broadly synchronous moisture fluctuations in sawn and split shingles, indicating a strong response to shared exposure conditions (Figure 5A). Both exhibited repeated wetting peaks followed by decreases in moisture content. The substantial overlap between the curves suggests that manufacturing method had a relatively modest influence compared with temporal variation in exposure. No clear, sustained increase in baseline moisture content was apparent from visual inspection of the monitoring series.

Across 3164 measurements per shingle type, mean moisture content was 17.5% for sawn shingles and 18.0% for split shingles. Median values were 16.9% and 17.7%, respectively. The slightly higher mean and median for split shingles agree with their greater wetting in the laboratory. In both cases, the mean exceeded the median, consistent with occasional high-moisture observations extending the upper tail of the distribution.

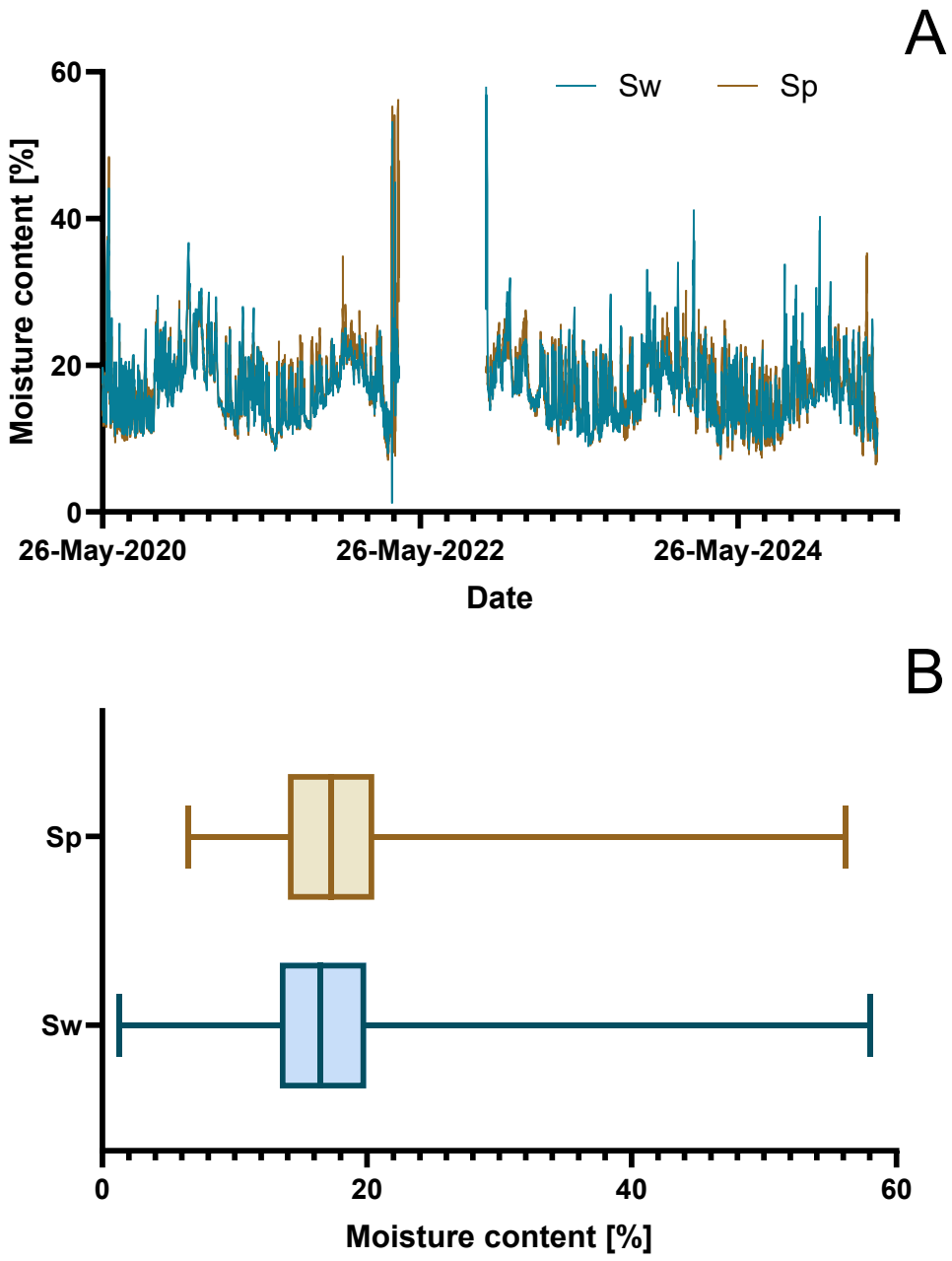

Figure 8: Moisture content of wood shingles in the monitoring period (A) and box-and-whisker plot representation of 3164 moisture measurements in a column graph (B).

Threshold exceedances provided a more differentiated comparison. Split shingles exceeded 20% moisture content in 29.6% of measurements, compared with 24.5% for sawn shingles—a difference of 5.1 percentage points. However, exceedances of 25% were nearly identical, at 4.5% and 4.7%, respectively. Above 30%, sawn shingles had a slightly higher proportion of observations than split shingles, 1.3% versus 0.9%. Consequently, the more frequent moderate wetting of split shingles did not translate

into more frequent exceedance of the highest thresholds. However, the statistical analysis revealed that the sawn shingles have statistically significant (<0,0001) lover MC than split shingles.

These indicators suggest broadly comparable field moisture performance, with sawn shingles typically slightly drier but no consistent advantage across all moisture thresholds. Threshold exceedances describe exposure to elevated moisture rather than directly measuring decay: biological consequences also depend on temperature and the duration and continuity of wet periods. Moreover, repeated observations characterise temporal behaviour and should not be treated as independent specimen replicates. The field results therefore provide no evidence that splitting alone ensures superior moisture performance under the investigated exposure conditions.

Elemental characterisation of wooden roofs and surface treatments of wooden roofs in Velika Planina

The 30 investigated cabins were unevenly distributed across the Velika Planina area, forming distinct groups within a mosaic of open pastures and forest. The largest concentration occurred around Gojška planina, with additional clusters near Mala Planina and the Marija Snežna chapel on Velika Planina. Cabins 17 and 18 occupied more dispersed positions towards the northeastern pasture margins, whereas cabins 1, 29, and 30 were situated within or alongside the forested eastern and southern margins. This arrangement reflects a pastoral settlement pattern in which buildings cluster near grazing areas and connect via local paths. Spatial proximity also suggests similar exposure conditions, so differences in roof chemistry, moisture content, and deterioration should be interpreted considering location, elevation, and forest shelter (Figure 9).

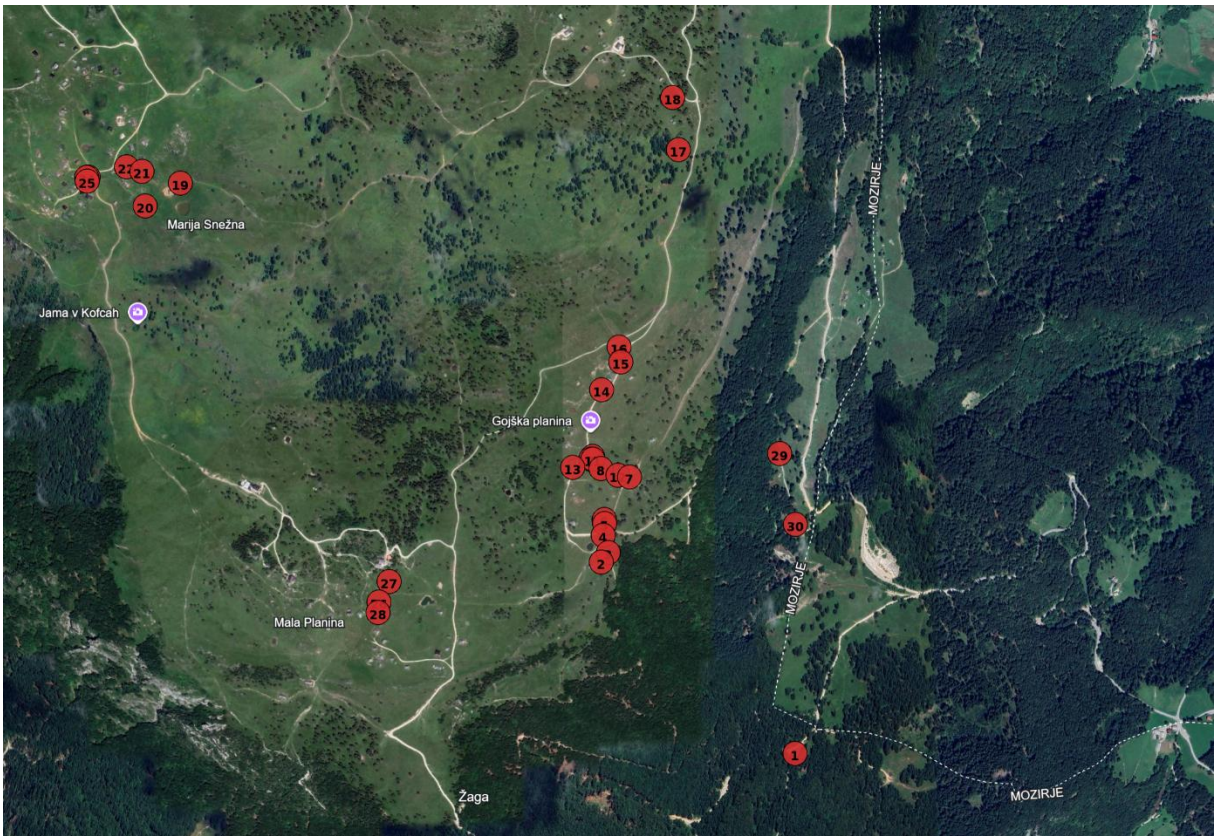

Figure 9: Cabins in Velika Planina, where chemical analysis of shingles was performed

Microscopic examination revealed a dark, irregular surface deposit containing accumulated dust and particulate material on the investigated shingles (Figure 10). Based on the visual appearance, reported treatment history, and XRF results, this observation supports using waste machine lubrication oil as a roof treatment. The shingle cross-section and micro-XRF maps showed that iron (Fe) and sulfur (S) were concentrated predominantly near the exposed surfaces, with comparatively weak signals in the interior (Figure 11). These distributions indicate superficial accumulation of treatment-associated constituents rather than uniform penetration through the shingle, as typical for superficial treated wood [21]. However, elemental maps trace measured elements rather than the full organic oil fraction; consequently, they show limited penetration of these constituents without excluding penetration of some hydrocarbon components.

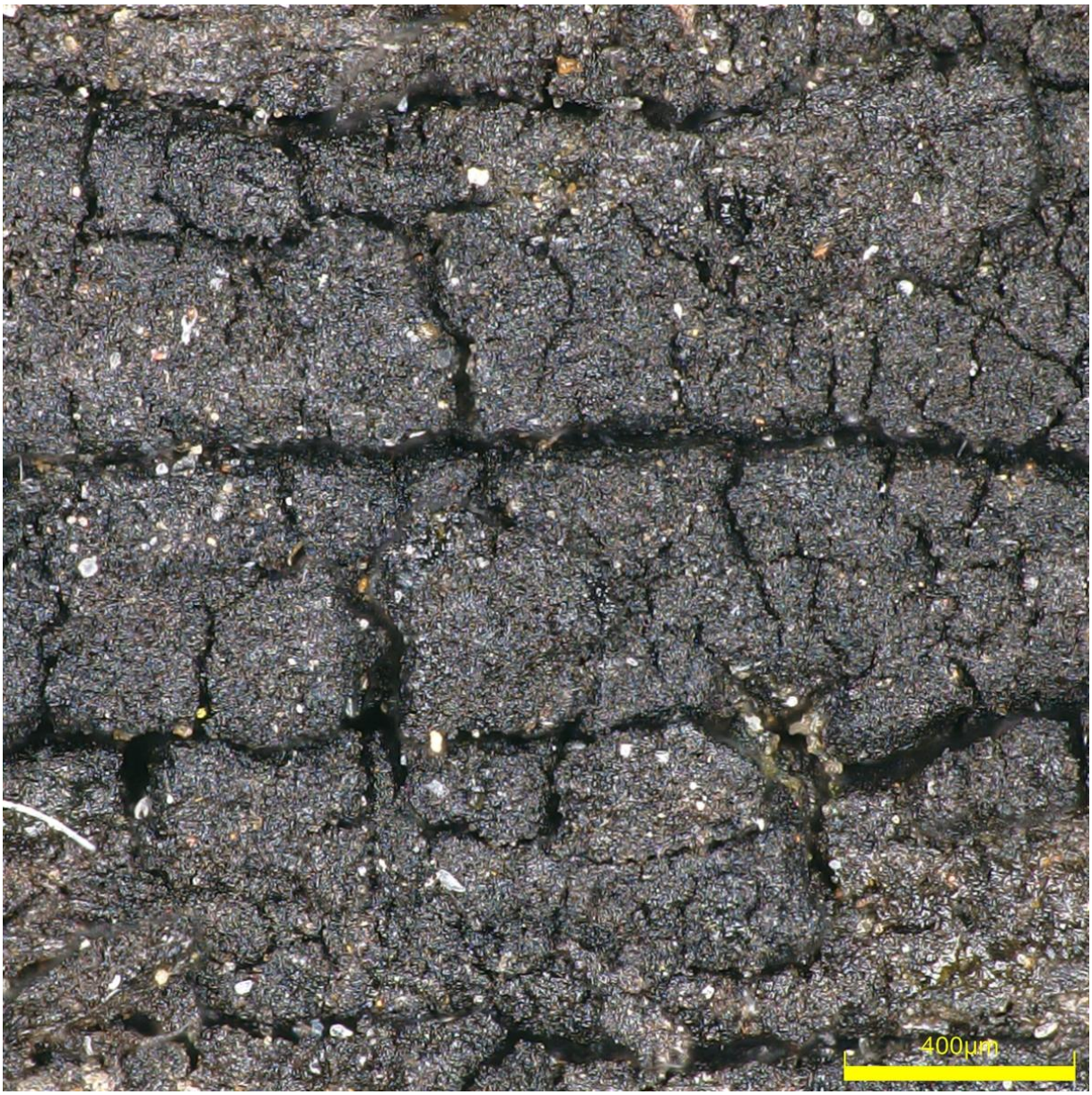

Figure 10: Waste machine oil deposits, mixed with dust and dirt on the surface of wooden roofs on the cabin at Velika Planina.

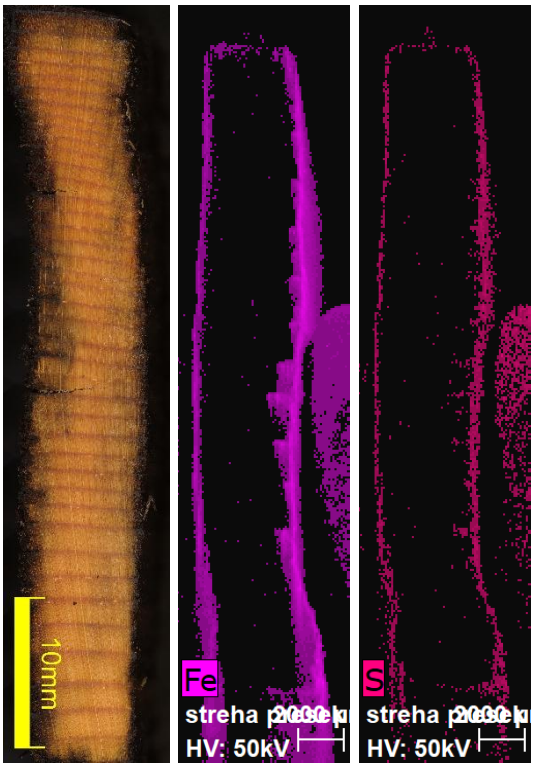

Figure 11: Cross-section of wooden shingle and microdistribution of Fe and S in wooden shingle on the cabin at Velika Planina.

The XRF spectra contained prominent signals associated with Ca, Fe, Zn, and S, alongside other elements (Figure 12). Their combined occurrence is consistent with a mixture of lubricating-oil residues, mineral particles, and environmental deposits. Zn is particularly relevant because zinc-containing additives commonly occur in lubricating oils, while Fe can originate from machinery wear and external contamination [22]. Nevertheless, none of these elements alone provides an unequivocal fingerprint of waste oil, and interpreting them requires comparison with untreated wood, coating formulations, and background deposits. We identified waste lubricant oil through visual examination, which enabled us to validate measurements.

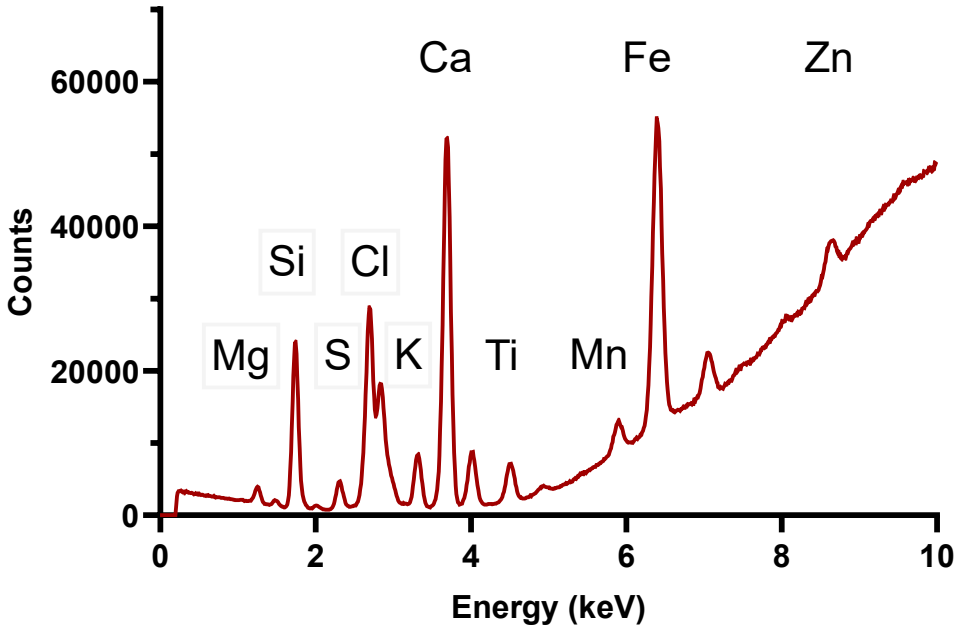

Figure 12: Typical XRF spectra of wooden shingles treated with waste machine oil

PCA provided a useful exploratory means of distinguishing roofs according to their reported surface treatment (Figure 13). Untreated observations formed a relatively compact group, whereas oil-treated observations extended predominantly towards negative PC2 scores. The separately coated observations were displaced strongly along positive PC1. The loading plot identified Fe as the dominant contributor along PC1, while S and K contributed strongly towards negative PC2; P contributed to the same general direction but less strongly (Figure 14). Thus, the separation of oil-treated observations was associated primarily with the multielement pattern involving S and K, whereas the pronounced Fe contribution was more closely associated with the separately coated group. K should be interpreted cautiously because it can also originate from the wood and other deposits.

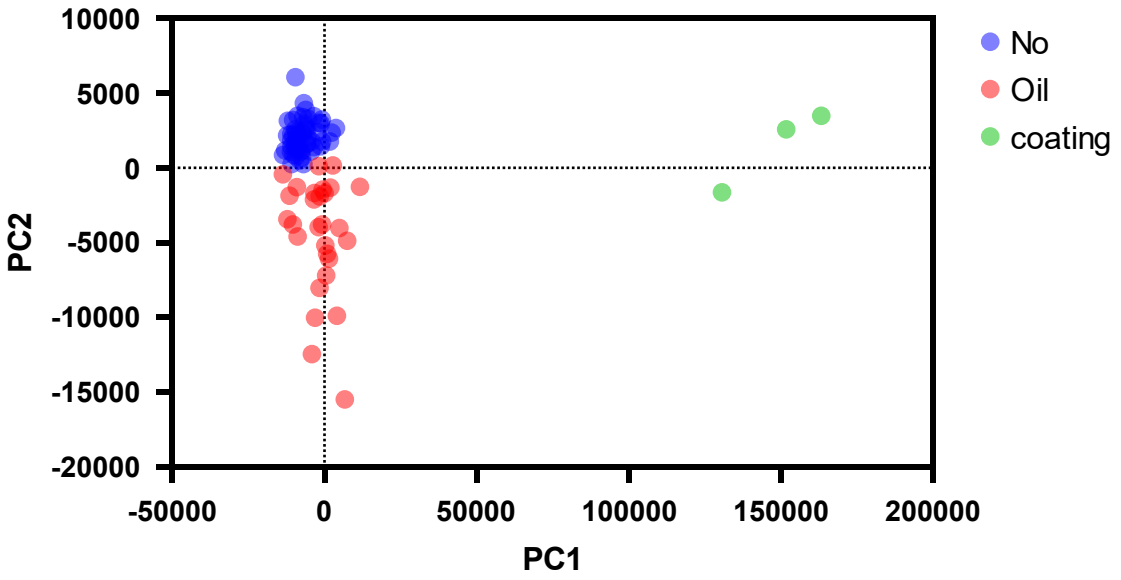

Figure 13: Results of the Principal Component Analysis (PCA) clearly distinguish the oil-treated roofs from untreated ones.

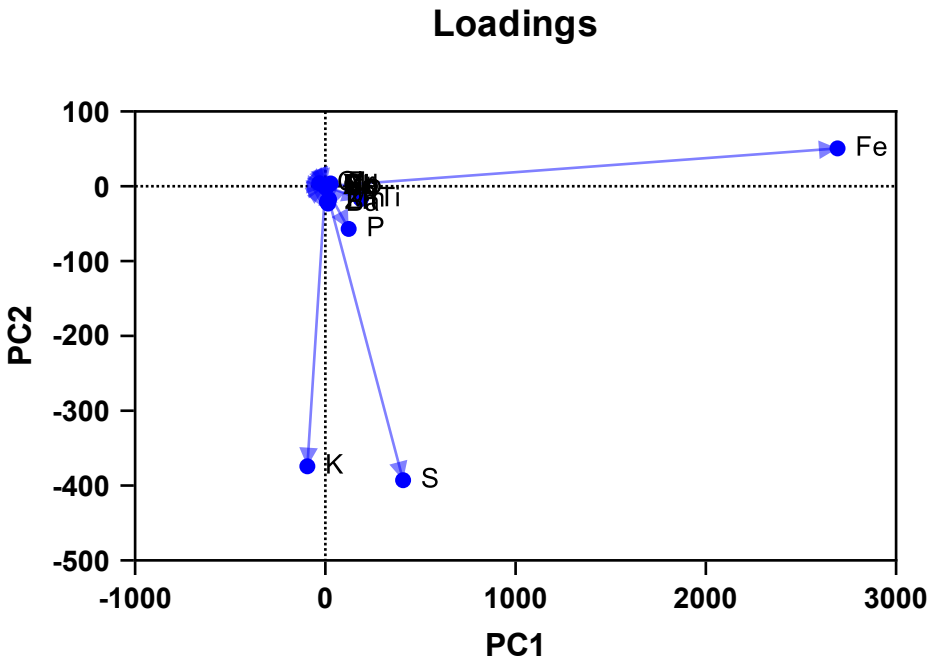

Figure 14: Key elements that contribute to the differences in PC1 and PC2

The correspondence between reported oil treatment and PCA scores demonstrates the potential of XRF combined with multivariate analysis as a rapid screening approach for identifying roofs requiring closer investigation. Its principal advantage is the integration of several elemental signals rather than reliance on one marker [23]. However, PCA is an exploratory ordination method, and the observed separation does

not establish classification accuracy for previously unexamined roofs. Independent validation would be required before using the approach as a definitive identification procedure.

The spread of oil-treated observations towards the untreated group suggests variation in the quantity or composition of retained residues. Progressive weathering and loss of treatment constituents through leaching or particle wash-off are plausible explanations for this gradient. Differences in application rate, oil composition, treatment age, and surface contamination could produce similar patterns. The gradient therefore supports a hypothesis of residue depletion.

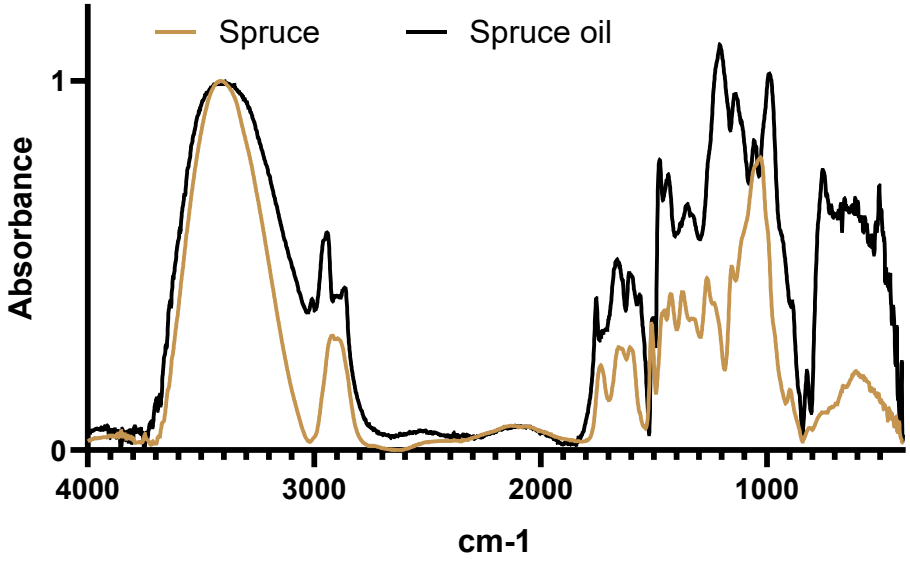

Figure 15: FTIR spectra of reference wood and waste oil-treated wood

The complexity of the surface system, likely containing traces of timber, waste lubricating oil, and environmental contaminants, makes interpreting the DRIFT results difficult. Both specimens show a strong O-H band at 3300 cm^{-1}, along with the typical C-H bands between 2940 and 2860 $cm^{-1,}$ but the C-H bands in the lubricating oil-treated wood shingles are much more pronounced, indicating a stronger presence of likely free C-H-containing substances. The lubricating oil-treated specimen also has an additional weak band at 3010 cm^{-1}, which is absent in the spectra of neat timber (*Picea abies*); the additional band likely represents hydrogen bound to an unsaturated carbon bond present in aromatics like polycyclic aromatic hydrocarbons (PAHs). Further down the spectral range, the lubricating oil-treated specimen shows a sharp band at 1753 cm^{-1}, likely from oxidised products in the waste lubricating oil, particularly ester

bonds, while neat timber shows a band at 1735 cm^{-1}, attributed to hemicelluloses. Furthermore, two bands at 1470 cm^{-1} and 1350 cm^{-1} indicate the presence of lubricating oils, typically assigned to short-chain hydrocarbons and C-H branching vibrations containing methylene groups [24] . Furthermore, both specimens show a strong region between 1700 cm^{-1} and 1600 cm^{-1}, which we attribute to aromatic compounds. In this case, it is difficult to tell whether these compounds result from lignin in the wooden shingles or from the waste lubricating oil surface treatment, as both major bands overlap well, but the bands in the lubricating oil are more intense. Interestingly, the roof shingle shows an additional band at 1562 cm^{-1} that is absent in the neat spruce spectra. This is likely due to metal carboxylate salt formation (COO^- stretching), likely a zinc carboxylate salt [25]. Between 1200 and 1000 cm^{-1} we can observe strong bands belonging to oxygenated species (C-O). For wood specifically, these are tied to glycosidic bonds in cellulose [26]. At the lower end of the spectrum, bands around 980 cm^{-1} indicate C=C bonds from aromatics, and bands at 820 and 750 cm-1 indicate C-H bonds. These are much less pronounced in wood, indicating that additional material containing these has been added to the surface of these shingles.

Despite this distinction, the surface accumulation represents an environmental concern because the deposits remain directly exposed to rainfall and weathering. Mobilisation of oil-associated substances could transfer contaminants to runoff and surrounding soils, with potential subsequent transport towards groundwater. Used motor oil is persistent, degrades slowly, and can contain toxic chemicals and metals; its inappropriate release can contaminate soil and water resources [27]. Accordingly, application to rain-exposed wooden roofing should be regarded as an environmentally unsuitable treatment practice.

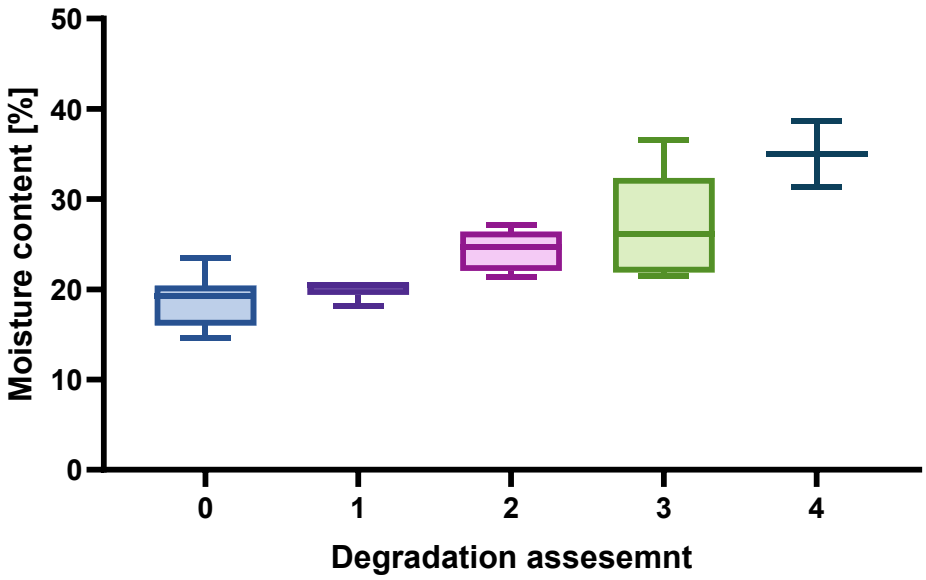

Figure 16: Influence of conditions of wood shingles on wood moisture content

In addition to the XRF measurements, we have visually assessed the shingle degradation and measured wood moisture content. Shingle deterioration was associated with progressively higher wood moisture content (Figure 8). Mean moisture content increased from 19.0% in condition class 0 to 20.0%, 24.3%, 26.9%, and 35.0% in classes 1–4, respectively. This monotonic pattern indicates a close relationship between poorer shingle condition and greater moisture content, although the most deteriorated class was represented by only two cabins.

The relationship is consistent with feedback between wetting and biological deterioration. Moisture supports fungal activity, while degradation can modify the pathways through which liquid water enters and moves within wood [28]. Experimental research has shown increased short-term water uptake in spruce after initial brown-rot exposure, though the response depends on decay type and stage [29]. Consequently, partly decayed shingles may absorb more water during rainfall, promoting conditions favourable for further deterioration. This creates a potential spiral of degradation in which moisture facilitates decay and decay increases susceptibility to subsequent wetting. Laboratory studies confirmed a similar relationship, and it was evident across all wood species investigated [28,29]. This pattern is also used commercially for bio-incising prior to wood impregnation [30,31].

The field observations support this feedback interpretation but do not establish its direction or rate. Roof age, treatment, exposure, shading, and measurement conditions

may influence both moisture content and deterioration. Nevertheless, the results underline the importance of preserving drainage and drying capacity and replacing severely deteriorated shingles before local damage develops into sustained moisture accumulation.

Conclusions

- Citizen science documented 130 structures with wooden roofing, predominantly in Alpine and pre-Alpine Slovenia. Pastoral buildings accounted for 40.8% of records, highlighting the link between wooden roofing and mountain grazing heritage.
- Wood was reported among the wall materials in 86.6% of structures with available information. Wooden roofing also occurred on masonry buildings and served agricultural, residential, religious, and recreational functions.
- Remote mapping identified approximately 280 candidate wooden-roof features in Velika Planina. It complemented citizen science by extending spatial coverage, although candidate features require verification and cannot be equated directly with individual buildings.
- Split shingles exhibited greater wetting during laboratory immersion and spraying. Outdoor moisture indicators were broadly comparable between manufacturing methods, providing no consistent evidence that splitting alone ensures superior moisture performance.
- XRF combined with PCA distinguished reported treatment groups and showed promise for screening oil-treated roofs. Microscopy and micro-XRF indicated that treatment-associated constituents accumulated predominantly at the surface.
- Waste lubricating oil application represents an environmentally unsuitable maintenance practice. Surface residues can become a source of contaminants, but leaching and groundwater impacts require direct measurement.

- Greater shingle deterioration coincided with higher moisture content, consistent with feedback between wetting and decay. Conservation should prioritise drainage, ventilation, inspection, and timely replacement of deteriorated shingle.

Data availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

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Clinical Trial Number Not applicable

Informed Consent Statement The citizen science component of this study on wooden roofs was conducted anonymously, and no personal information or data identifying individual participants were collected. Participants were informed that the information they provided would be used for research, mapping, and scientific publication.

Informed consent was obtained through participation: by contributing to the study, participants agreed to these uses of the information provided.

Ethics and Consent to Participate declarations

This study investigated wooden roofs and wood materials and did not involve human participants as research subjects, human biological material, or live vertebrates. Citizen science contributors provided observations about buildings and their roofs; no personal characteristics, opinions, or behaviour of contributors were analysed. The study was therefore considered outside the scope of research involving human participants, and no ethics committee approval or formal waiver was sought or obtained.

The wood materials used in this study were purchased or received as donations and were not cultivated specifically for the research. All wood originated from sustainably managed forests in Slovenia, and its procurement was not associated with illegal logging or deforestation.

Consent to Publish declaration: Not applicable

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflict of Interest The authors have no personal interest or relationship that affects the publication of this manuscript.

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