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ORIGINAL ARTICLE

Weather-induced colour change in wood: material response in different European locations

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Abstract

This study investigates the colour evolution of Norway spruce wood during one year of natural weathering across multiple European locations as part of a Round Robin experiment. Colour measurements (*CIE Lab*) were performed on samples with monthly-resolved exposure duration to quantify discolouration and determine total colour change (ΔE). The results show that weathering induces rapid colour modification, with the most pronounced changes occurring within the first month of exposure. A clear two-stage behaviour was identified: an initial colour-enrichment phase, characterised by increases in *CIE a* and *CIE b*, followed by progressive decolouration and greying, reflected primarily through decreases in *CIE L*. Although the fundamental mechanisms of photodegradation were consistent across all sites, the rate and extent of discolouration varied substantially with local climatic conditions. Samples exposed in Turkey exhibited the highest ΔE values, whereas those in the UK showed the lowest. This difference is consistent with expected climatic variations in solar radiation, moisture conditions, and temperature fluctuations between the two locations, which are known to influence weathering kinetics. The dataset provides a robust basis for linking colour change and its dynamics with site-specific climate parameters enabling the development of a dedicated dose-response model.

1 Introduction

Wood is widely used in exterior applications due to its sustainability benefits, versatility, and aesthetic qualities. However, when exposed outdoors, wood surfaces undergo progressive deterioration driven by environmental factors. Weathering of wood is generally defined as the surface degradation that develops during exposure to outdoor conditions, resulting in changes in appearance and surface integrity (Evans 2012; Reinprecht et al. 2018; Aydın et al. 2025; Mi et al. 2023; Mastouri et al. 2023). Among the governing mechanisms, ultraviolet (UV) radiation plays a primary role in initiating photochemical degradation of lignin, which leads to surface discolouration and subsequent material modification (Feist and Hon 1984). In practice, natural weathering is a multi-factor process in which solar radiation, moisture cycling, temperature, and biological activity interact to produce progressive colour change and surface ageing (Derbyshire et al. 1995; Tolvaj et al. 2016; Varga et al. 2017; Kropat et al. 2020).

In addition to the general mechanisms described above, the influence of local and regional climate conditions influences the weathering behaviour of wood. Climatic parameters such as temperature, relative humidity, precipitation patterns, and duration of wetness affect the relative contribution of photochemical, physical, and biological degradation processes (Niklewski et al. 2024; Kropat et al. 2020). In continental European climates, for example, frequent moisture fluctuations and moderate temperatures promote fungal colonisation, making fungal discolouration a dominant contributor to colour changes observed on exterior wooden façades (Poohphajai et al. 2023). Under such conditions,

Extended author information available on the last page of the article

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abiotic weathering progressively alters the physical, chemical, and visual characteristics of wood surfaces, creating favourable conditions for microbial colonisation and subsequent biological degradation (Kržišnik et al. 2018; Buchner et al., 2019). Furthermore, biological interactions beyond microbial activity may also influence surface degradation; for instance, insects such as wasps can mechanically modify weathered wood by collecting exposed cellulose fibres for nest-building, thereby accelerating surface erosion (Hill, 2022). These climate-dependent and location-specific factors highlight the need to interpret weathering results within their environmental context and caution against direct generalisation across different climatic regions.

In practical applications, changes in wood surface appearance can influence user acceptance, trigger maintenance actions, and affect the perceived service condition of exterior wood components. The extent and rate of these changes depend on the type of material considered, including untreated wood, preservative-treated wood, modified wood, and surface-coated systems, each of which exhibits distinct weathering behaviour and colour stability. The present description primarily refers to uncoated wood surfaces, where colour changes are directly governed by environmental exposure and intrinsic material properties. In particular, uncertainty in the speed and pattern of colour change has been identified as a factor limiting confidence in the use of natural wood in exterior design (Sandak et al. 2021). Consequently, improving the understanding of weathering behaviour remains important for both material optimisation and service-life planning of wood used outdoors (Jirouš-Rajković and Miklečić 2021).

The evolution of wood colour during outdoor exposure has been widely investigated using the *CIE L*a*b** colour space, which enables quantitative tracking of surface appearance over time. Previous studies consistently report that the early stages of weathering are characterised by rapid photochemical modification of surface constituents, particularly lignin and extractives, leading to pronounced shifts in colour coordinates (Pandey 2005). The magnitude and direction of these changes are strongly influenced by the spectral composition of incident radiation, indicating that light quality plays a critical role in governing photodegradation pathways and the resulting visual response of wood surfaces (Oltean et al. 2008; Tolvaj and Mitsui 2005; Živković et al. 2014). As exposure continues, the colour trajectory typically transitions from the initial chromophore-driven modification phase toward progressive surface greying associated with ongoing lignin breakdown and surface erosion (Lampela et al. 2025; George et al. 2005). However, the rate and extent of these changes are not uniform and have been shown to vary substantially depending on environmental conditions and exposure duration (Evans et al. 2005).

Although the fundamental mechanisms governing wood colour change during outdoor exposure are well documented, much of the existing experimental evidence has been generated under controlled laboratory conditions or within single-site natural weathering studies. Several investigations have focused on comparing artificial and natural ageing responses or establishing correlations between laboratory tests and outdoor exposure, typically within a limited climatic context (Sandak et al. 2021; Kržišnik et al. 2018; Liu et al. 2019; Schnabel et al. 2009; Nguyen et al. 2019). While these studies have significantly advanced understanding of photodegradation behaviour, they also highlight that colour evolution under natural conditions can exhibit greater variability than that observed in accelerated environments (Petrillo et al. 2019), complicating direct comparison across studies and exposure scenarios.

As a consequence, quantitatively comparable datasets that capture wood colour evolution across multiple climates using harmonised natural exposure protocols remain limited. This lack of cross-climate consistency constrains the ability to robustly assess how environmental variability influences the kinetics and trajectory of colour change in exterior wood. Given the continued and often untreated use of wood in outdoor applications (Oberhofnerová et al. 2017), there is a clear need for coordinated multi-site investigations that enable systematic evaluation of climate-dependent weathering behaviour under comparable conditions. In this context, the key advancement of the present study lies in the use of a harmonised, Round Robin natural weathering protocol applied simultaneously across multiple European climates. By standardising material selection, sample preparation, exposure configuration, and evaluation procedures, this approach enables direct quantitative comparison of colour evolution across sites, thereby reducing methodological variability that has limited previous studies. This provides a more robust basis for assessing climate-driven differences in both the kinetics and trajectories of wood colour change under real outdoor conditions. Norway spruce was selected as a model species due to its widespread use in exterior applications across Europe, particularly in façades and cladding, as well as its relatively low natural durability and high susceptibility to photodegradation and moisture-induced changes. These characteristics make it especially sensitive to environmental exposure and, therefore, well suited for detecting climate-dependent differences in weathering behaviour. At the same time, its practical relevance ensures that the findings are directly applicable to commonly used construction materials.

The aim of this study was to systematically evaluate the climate-dependent colour evolution of Norway spruce wood during natural weathering across multiple European locations using a harmonised Round Robin exposure design.

This establishes an empirical foundation for future dose-response modelling of weather-induced appearance change under realistic service conditions.

2 Materials and methods

2.1 Experimental sample preparation

All specimens used in this study were prepared from a single Norway spruce (*Picea abies [L.] Karst.*) log harvested in Northern Italy (Val di Fiemme, Dolomite Mountains) and supplied by a local sawmill in Mezzocorona. The tree was approximately 100 years old at the time of harvesting and had a stem diameter of 55 cm. The air-dry wood density was 420 kg/m^3. The specimens preparation procedure is illustrated in Fig. 1. First, a 50 cm long section was extracted from the trunk at breast height (1). The log was then radially split with an axe (2) to follow the natural spiral grain deviation. The resulting wedges were planed (3) to obtain a flat reference surface and subsequently re-sawn into 6 mm thick lamellae (4). The lamellae were then trimmed to a width of 30 mm using a circular saw (5). Each stick was thickness-planed (6) to a final thickness of 5 mm, after which the final reference surface was produced using a super-surfacer planer (Marunaka). Finally, the sticks were cut to a length of 80 mm using a circular saw (7).

A specimen thickness of 5 mm was selected to ensure a surface-dominated response to weathering while maintaining sufficient dimensional stability for handling and multi-site exposure. Specimens were prepared from randomly selected boards without deliberate separation of sapwood and heartwood, resulting in a material composition representative of commercially available mixed-sawn timber. No coatings or protective treatments were applied to any specimen. The end-grain surfaces were sealed with aluminium foil with adhesive to limit moisture uptake through the cross-sections. Minor damage to the sealing occurred during exposure but did not affect the exposed surface used for measurements. After manufacture, all samples were conditioned at 20 °C and 60% RH in the absence of UV radiation. Before distribution to partners, each piece underwent reference colour measurements and colour image scanning.

Despite efforts to prepare the material as uniformly as possible, natural wood heterogeneity remained evident. As illustrated in Fig. 2, variation in growth-ring width and anatomical structure was observable among specimens. For this reason, subsequent sample assignment, coding and distribution into location batches were randomized.

Each sample was assigned a unique identification code composed of a three-digit institutional number and a letter denoting the expected exposure duration. Barcodes were added to enable automated tracking. A complete set of pieces (codes ranging from M to X) was prepared for each participating partner and shipped prior to the start of the Round-Robin test.

Round-Robin Test.

A coordinated interlaboratory Round-Robin test was conducted within the framework of COST Action FP1006 to develop a harmonized dataset on the natural weathering behaviour of wood. The initiative was led by the SWORFISH project team at the Trees and Timber Institute of the National Research Council of Italy (IVALSA/CNR, San Michele all'Adige, Italy). The objectives were to evaluate the behaviour of identically prepared samples under a range of climatic conditions and to assess methodological comparability among laboratories.

Multiple European institutions participated voluntarily. Table 1 lists all exposure locations together with the corresponding Köppen climate classifications (KCC) (Beck et al. 2018) and simplified climate descriptors. For clarity, the Köppen-Geiger classification is complemented by a simplified grouping into broader climate types (temperate, continental, Mediterranean), reflecting the transitional nature of

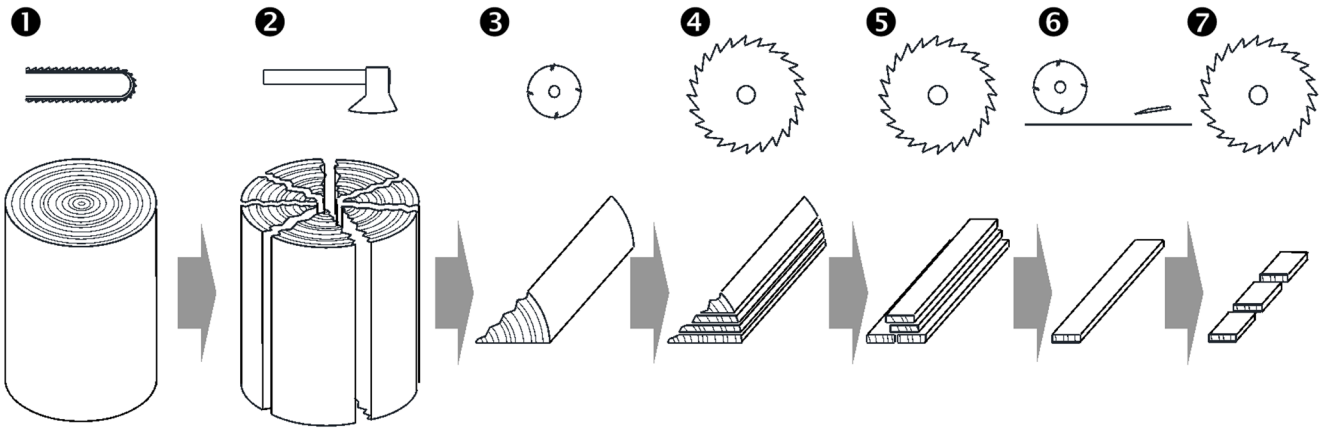


Fig. 1 Schematic representation of sample preparation

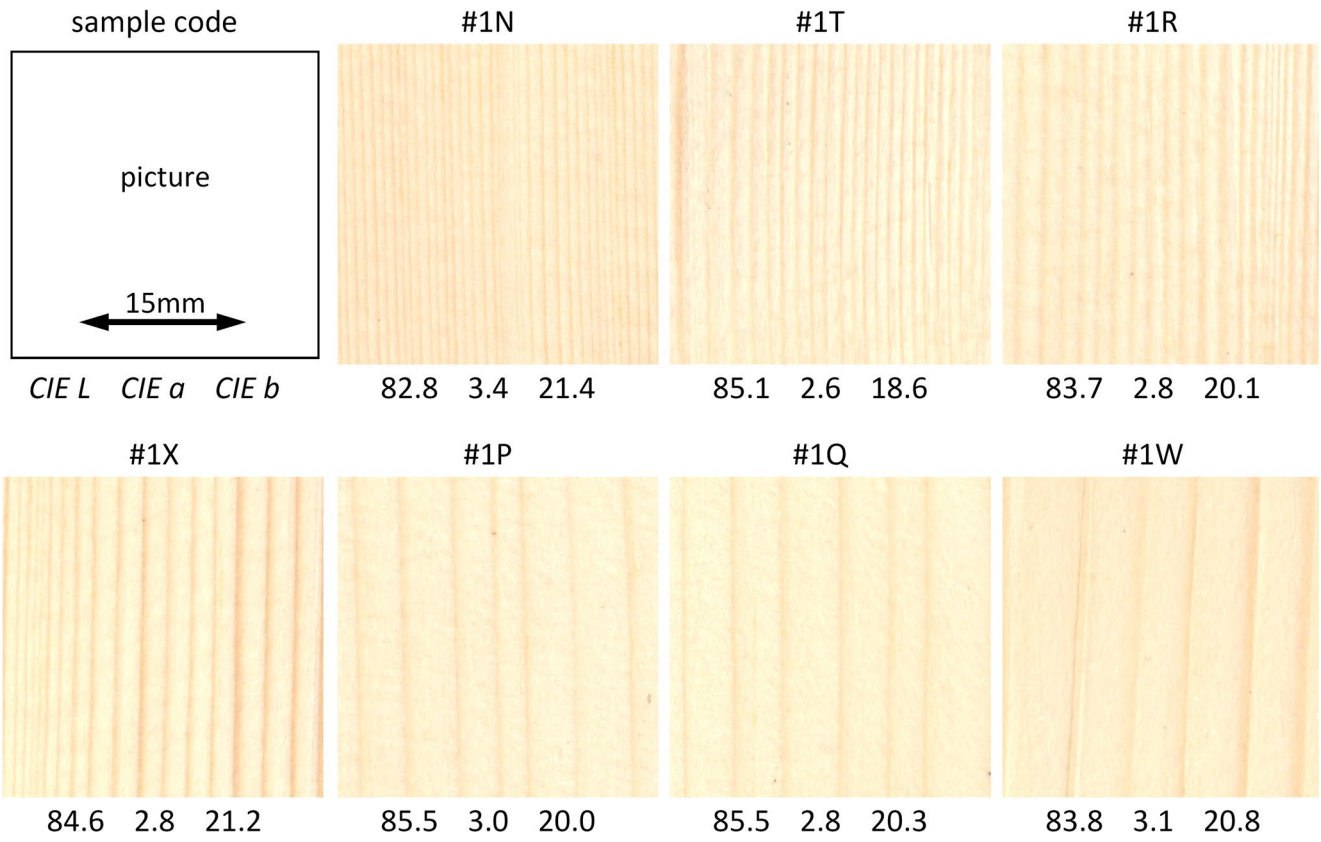


Fig. 2 Images of the experimental samples processed from a single Norway spruce log. Note: the upper text on each image corresponds to the sample code, while three numbers on the bottom to the CIE L, CIE a and CIE b colour coordinates measured on the surface of that sample

several sites. Scheffer Climate Index (SCI) values reported here are based on harmonised long-term climate normals and are intended for relative comparison of biological decay/climate exposure potential across sites (Brimblecombe and Richards 2023). Climate data represent long-term multiannual climate normals derived from established climatological databases and national meteorological services and are used for site characterization rather than representing conditions during the specific exposure period. Although site-specific UV radiation was not directly measured, regional differences in solar exposure are expected to follow known climatic gradients across Europe, with higher radiation levels in Mediterranean regions and lower levels in Atlantic and northern climates. Central coordination, including sample preparation, reference measurements, data integration, logistics, and communication, was managed by IVALSA/CNR. It should be noted that two replicate sample sets were exposed in San Sebastian, and a few specimens were lost during exposure due to wind, animals, and other factors.

2.2 Exposure setup and sample retrieval schedule

The study was conducted over a full calendar year beginning in spring 2014, ensuring that samples experienced complete seasonal climatic variation at all participating sites. Partners installed the samples following a unified protocol: all specimens were mounted outdoors at a 45° inclination facing south, with unobstructed exposure to direct solar radiation, rain, wind, and all natural weathering factors. The inclination angle of 45° was selected in accordance with common natural weathering standards (e.g., EN 927-3). This orientation provides a balanced exposure condition that promotes effective wet-dry cycling and runoff while ensuring comparability across exposure sites. Installation systems were designed to prevent mechanical damage, contamination, or vandalism. This standardized configuration ensured comparability of exposure conditions across contrasting climates. Representative photographs of sample stands are shown in Fig. 3.

2.3 Post-exposure handling and storage

Twelve wood samples were retrieved manually at monthly intervals. In addition, the first thin sample (code A), collected on the day the test began, served as the reference specimen and shared the same material history but was not weather-exposed. The retrieval schedule was identical for all partners, and in most cases, the collection dates were

Table 1 Locations where samples were exposed to natural weathering

Sample set number	Country	City	KCC	SCI	Climate Description (multiannual mean temperature range [°C]), yearly precipitation in mm/year
#1	Reference	–	–		–
#2	Austria	Kuchl	Cfb	40–50	Oceanic (–2 °C to 19 °C), 1913
#3	Belgium	Brussels	Cfb	55–65	Temperate oceanic (4 °C to 19 °C), 807
#4	Germany	Göttingen	Cfb	50–60	Temperate fully humid (1 °C to 18 °C), 804
#5	Greece	Thessaloniki	Cfa	35–45	Humid subtropical (4 °C to 27 °C), 687
#6	Hungary	Sopron	Cfb	45–55	Marine west coast (0 °C to 21 °C), 764
#7	Italy	San Michele	Dfb	45–55	Humid continental (–2 °C to 19 °C), 1114
#8	Italy	Sporminore	Dfb	40–50	Humid continental (–2 °C to 19 °C), 1114
#9	Latvia	Riga	Dfb	55–65	Humid continental (–3 °C to 19 °C), 780
#10	Norway	As	Dfb	50–60	Humid continental (–4 °C to 17 °C), 837
#11	Poland	Nowe	Cfb	50–60	Marine west coast (–2 °C to 20 °C), 676
#12	Poland	Poznan	Cfb	50–60	Oceanic (–3 °C to 24 °C), 649
#13	Spain	Barcelona	Csa	45–55	Mediterranean (8 °C to 24 °C), 614
#14	Spain	Llieda	BSk/Csa	35–45	Semi–arid, Mediterranean (6 °C to 26 °C), 461
#15	Spain	Solsona	Cfb	40–50	Oceanic (–1 °C to 28 °C), 854
#16	Spain	San Sebastian #1	Cfb	60–70	Atlantic coastal oceanic (8 °C to 20 °C), 1476
#17	Spain	San Sebastian #2	Cfb	60–70	Atlantic coastal oceanic (8 °C to 20 °C), 1476
#18	Switzerland	Duebendorf	Cfb	55–65	Oceanic, Swiss Plateau (0 °C to 19 °C), 1124
#19	Switzerland	Biel	Cfb	50–60	Oceanic, Swiss Plateau (1 °C to 19 °C), 1470
#20	Turkey	Bartin	Cfa	80–90	Humid subtropical (4 °C to 23 °C), 842
#21	UK	Bangor	Cfb	60–70	Oceanic maritime (4 °C to 15 °C), 1085
#22	UK	Henfaes	Cfb	60–70	Oceanic maritime (4 °C to 15 °C), 1085



Fig. 3 Experimental stands with samples exposed to natural weathering at locations in San Sebastian (Spain), Nowe (Poland) and San Michele (Italy). Note: grey card was used as a reference for the image colour correction

synchronized, ensuring consistent exposure durations irrespective of geographic location.

Immediately after retrieval, specimens were placed in controlled conditions to avoid unintended post-weathering changes. This procedure ensured that the resulting dataset comprised samples representing well-defined cumulative weathering doses corresponding to monthly exposure increments. Recommended storage conditions were 20 °C and 60% RH in darkness, preventing additional UV exposure.

At the end of the one-year campaign, all samples were returned to IVALSA/CNR along with site-specific climatic records and a brief report documenting any deviations, handling notes, or additional analyses conducted by partner laboratories.

2.4 Weathered sample characterization

Upon return, all weathered samples were conditioned in a dark climatic chamber at IVALSA/CNR (20 °C, 60% RH). After thermodynamic equilibrium was reached and the difference in mass between two successive weightings separated by an interval of 1 day was less than 0.1%, specimens were analysed using a standardized protocol to ensure cross-laboratory comparability. To avoid introducing systematic bias, measurement order was randomized. This ensured that observed variability was attributable solely to climatic exposure conditions and exposure duration.

Colour measurements were performed using a Micro-Flash 200D spectrophotometer (DataColor International, Lawrenceville, USA) following the *CIE* $L^*a^*b^*$ colour space. Illuminant D65 and a 10° observer angle were used. Each specimen was measured at five randomly selected locations distributed across the weathered surface. Total colour difference ΔE was calculated from $\Delta CIE\ L^*$, $\Delta CIE\ a^*$, and $\Delta CIE\ b^*$ coordinates of the weathered sample (*d*) relative to its reference state (*ref*), according to Eq. 1 to 4.

$$\Delta L^* = L_d^* - L_{ref}^* \tag{1}$$

$$\Delta a^* = a_d^* - a_{ref}^* \tag{2}$$

$$\Delta b^* = b_d^* - b_{ref}^* \tag{3}$$

$$\Delta E = \sqrt{[(L_d^* - L_{ref}^*)^2 + (a_d^* - a_{ref}^*)^2 + (b_d^* - b_{ref}^*)^2]} \tag{4}$$

In addition to the colorimetric analysis, high-definition images of all samples were acquired using an HP G2710 colour office scanner (Hewlett-Packard). The scanning resolution was set to 600 dpi, and all automatic colour-correction algorithms and enhancement options were deliberately disabled. This procedure ensured that images could be directly compared across different stages of the weathering process.

All the results generated as a part of the Round robin test are available as a data set on the open repository (Sandak 2026).

3 Results

The initial appearance of the unweathered wood samples, shown in Fig. 2, reflects the typical light, yellowish colour of Norway spruce. The main variations arise from differences between earlywood and latewood, as well as from varying annual ring widths. Overall, the colour variation is minor, which is consistent with the CIE Lab colorimetric values determined for the presented samples.

In contrast, the images of wood exposed to natural weathering for one year at different Round Robin test locations (Fig. 4) reveal substantial differences. Variations in the extent of greying are clearly visible, together with other appearance changes. A prominent surface crack is observed on the sample from location #8 (Sporminore), representing a typical defect caused by repeated sorption-desorption cycles during weathering. Another atypical feature, an uneven goldish discoloration, was noted on sample #20 (Bartin). Detailed examination confirmed that this pattern resulted from wasp activity: the insects had fed on carbohydrates present on the delignified surface of the weathered wood. This phenomenon was common in samples exposed in Turkey, where wasp activity was particularly high during the summer months.

Despite these localised discoloration patterns, the general trend across sites was a gradual shift towards a nearly uniform grey surface, although the rate and extent of greying varied considerably between locations.

While visual inspection provides valuable qualitative insight, an objective quantification of colour change during weathering is essential. For this reason, the evolution of colour parameters over time was analysed for all locations. The resulting trends for ΔL, Δa, and Δb are presented in Fig. 5. Additionally, the total colour difference ΔE was modelled using a third-degree polynomial fit, providing a time-dependent representation of colour alteration for each exposure site. The statistical significance of the fitting curves for each exposure location was assessed using the coefficient of determination (R^2), calculated from the regression between the measured ΔE values and the corresponding values predicted by the fitted model. For most exposure conditions, R^2 exceeded 0.85, indicating that the proposed functions provided a reliable description of the overall discolouration trends.

As shown in Fig. 5, sample #1 exhibits negligible colour changes throughout the entire period. This was expected, as these samples served as the reference and were not exposed to outdoor weathering, but only stored in a dark room. Thus, any deviation from zero reflects only the intrinsic natural colour variability of the wood and the measurement uncertainty. Two extreme cases can be identified among the weathered samples. Sample #22, exposed in the UK, showed the least degree of weathering, while sample #20 from Turkey exhibited the most pronounced colour change. Figures 6 and 7 provide systematic visualizations of the weathering progression for these two sites.

The third-degree polynomial fitting proved highly effective in identifying general trends and estimating the kinetics of discoloration. The results after 12 months of exposure, sorted according to ΔE values, are summarized in Fig. 8,

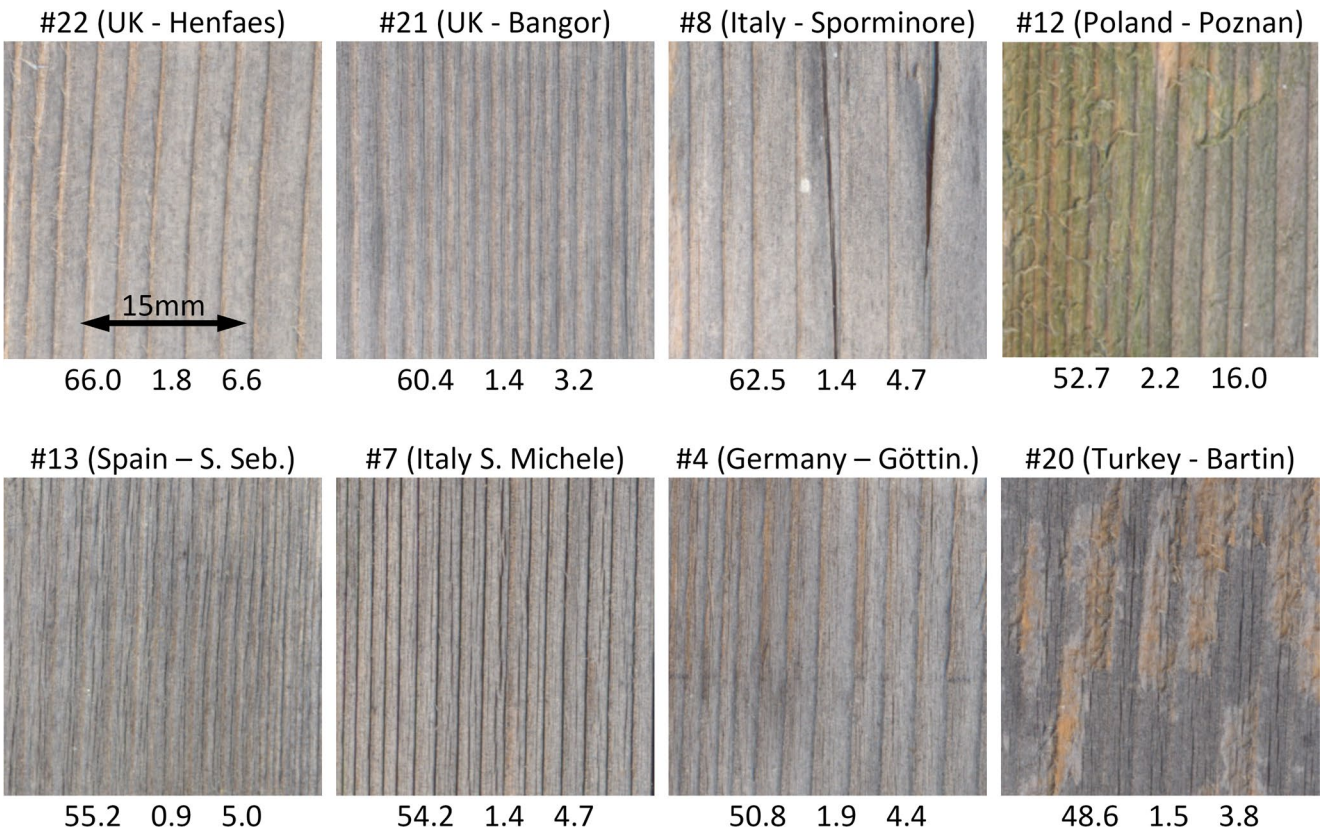


Fig. 4 Samples after 12 months exposure in different locations

together with the corresponding CIE *L*, *CIE a*, and *CIE b* components.

a)

4 Discussion

The results demonstrate that wood colour responds rapidly to natural weathering. As shown in Fig. 5, extensive colour changes occur within the first month of exposure, followed by a continued, though gradually decreasing, rate of change throughout the whole 12 month period.

The unweathered samples served as a control group for calculating *ΔE*. The *ΔE* values (Fig. 5d) confirm a sharp colour transition immediately after the first month of exposure. After this initial rapid change, the increase in *ΔE* becomes more gradual. A plateau is visible between months 4 and 10, which corresponds to the winter period (exposure began in June, placing the plateau from September to March). Reduced UV radiation, lower temperatures, and higher moisture during winter are known to slow photodegradation and chemical reactions responsible for colour change.

Several samples exhibited a reduction in *CIE L* after the first month, followed by a gradual decrease during the remaining exposure period (Fig. 5a). Only a few locations (#20 (Bartin), #18 (Duebendorf), #6 (Sopron), #12 (Poznan) showed a consistent increase in ΔE throughout the entire year. The decrease in *CIE L* of unprotected wood at the early stage of exposure indicates surface darkening caused by lignin degradation products, followed by fungal colonisation (Evans et al. 1992; Rowell 2005; Poohphajai et al. 2021).

The chromatic components *CIE a* and *CIE b* (Fig. 5b and c) also displayed a characteristic pattern, including a rapid increase during the first month, followed by a steady decrease, eventually stabilizing after approximately 6–7 months. The initial increase in *CIE b* is often associated with the degradation of lignin. Both *CIE a* and *CIE b* tended toward zero, indicating a loss of chromaticity and the development of a grey appearance. This transition reflects the typical sequence of wood surface photodegradation: initial colour enrichment due to extractive modification and lignin oxidation, followed by bleaching, leaching of coloured compounds, and finally surface greying. This behaviour is consistent with the underlying photodegradation mechanisms of wood (Aydın et al. 2026; Arpaci et al. 2021). Initial exposure to UV radiation leads to rapid lignin degradation at the surface, causing pronounced colour changes due to oxidation and the formation of chromophoric compounds (Feng et al., 2025). As these reactive lignin components

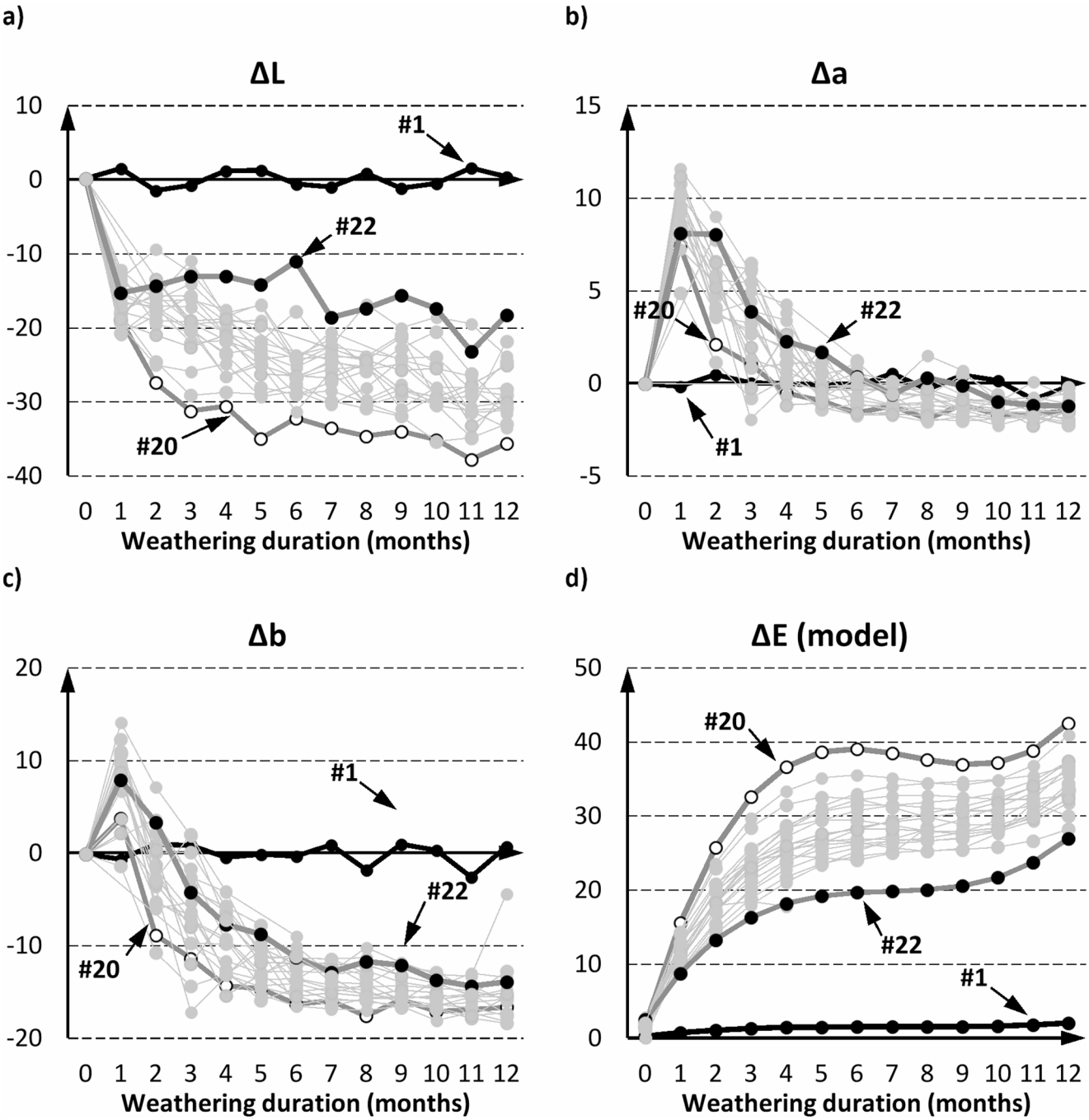


Fig. 5 Colour changes *ΔL***a**, *Δa***b**, *Δb***c** and *ΔE***d** of wood samples exposed to natural weathering for one year in different European locations. Note: *ΔE* values follow a third-degree polynomial interpolation model

are progressively depleted, the surface becomes enriched in cellulose and hemicellulose, which are more resistant to further photodegradation (Mitsui 2010). At the same time, degradation products may form a thin protective layer that partially shields the underlying material and slows down further reactions. The leaching of extractives and pigments during early weathering stages further contributes to bleaching and colour loss. Over time, as these easily degradable and colour-active components are removed or stabilised, the wood surface approaches a weathering equilibrium, resulting in a more uniform appearance and significantly reduced rates of colour change (Evans 2009; Sandak et al. 2024).

Correspondingly, the behaviour of *ΔL*, *Δa*, and *Δb* suggests that natural weathering proceeds through two distinct stages. Initial colour enrichment occurs at the first stage during the early weeks of exposure, where both *CIE a* and *CIE*

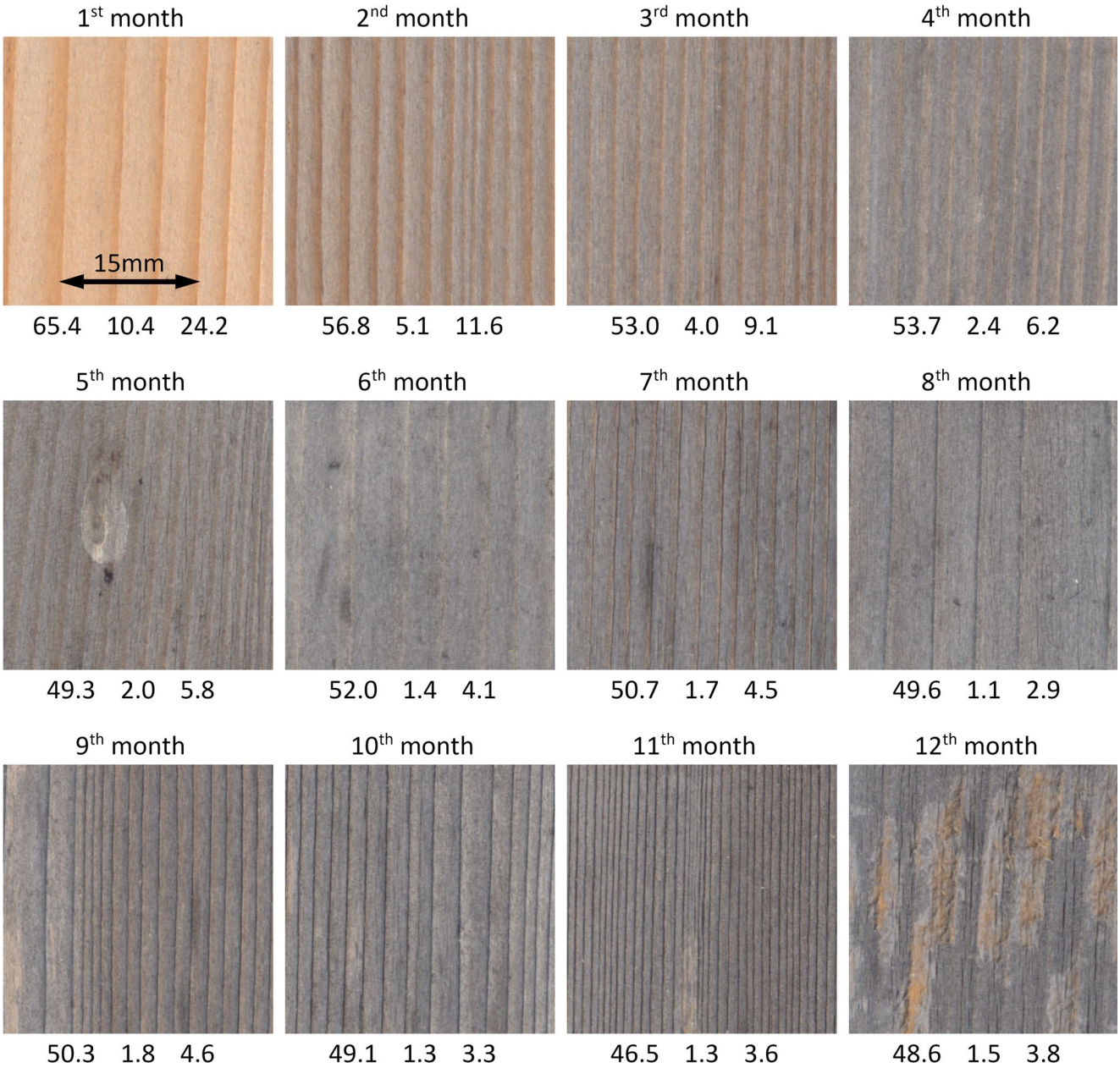


Fig. 6 Example of the appearance changes in wood samples exposed to natural weathering in Turkey (location #20)

b increase notably. The surface appears more reddish and yellowish due to the formation of chromophoric groups and migration of extractives (Pandey 2005). In the second stage, a progressive decolouration and greying are observed. In that stage, as exposure continues, ΔL decreases and samples become progressively greyer. In some samples, this greying begins so quickly that the colour-enrichment phase is visually overshadowed. This overlap explains the observed immediate drop in ΔL after the first month, where the onset of greying dominates the overall colour evolution. Visual inspection supports this interpretation. Samples showing a consistently decreasing ΔL (e.g., from location #20) became visibly grey after only one month of exposure.

Besides photodegradation, biological factors also contributed to colour changes (Gobakken et al. 2010; Hukka and Viitanen 1999). For example, at location #12 (Poznan), the Δb value increased sharply during the final month of exposure (Fig. 5c). This aligns with the images in Fig. 6, where substantial algal growth is visible on half of the sample surface. Such colonization increases colour values due to the pigmentation of biological organisms and therefore must be considered when interpreting Δb trends (Butina et al. 2023, Acquah et al. 2026).

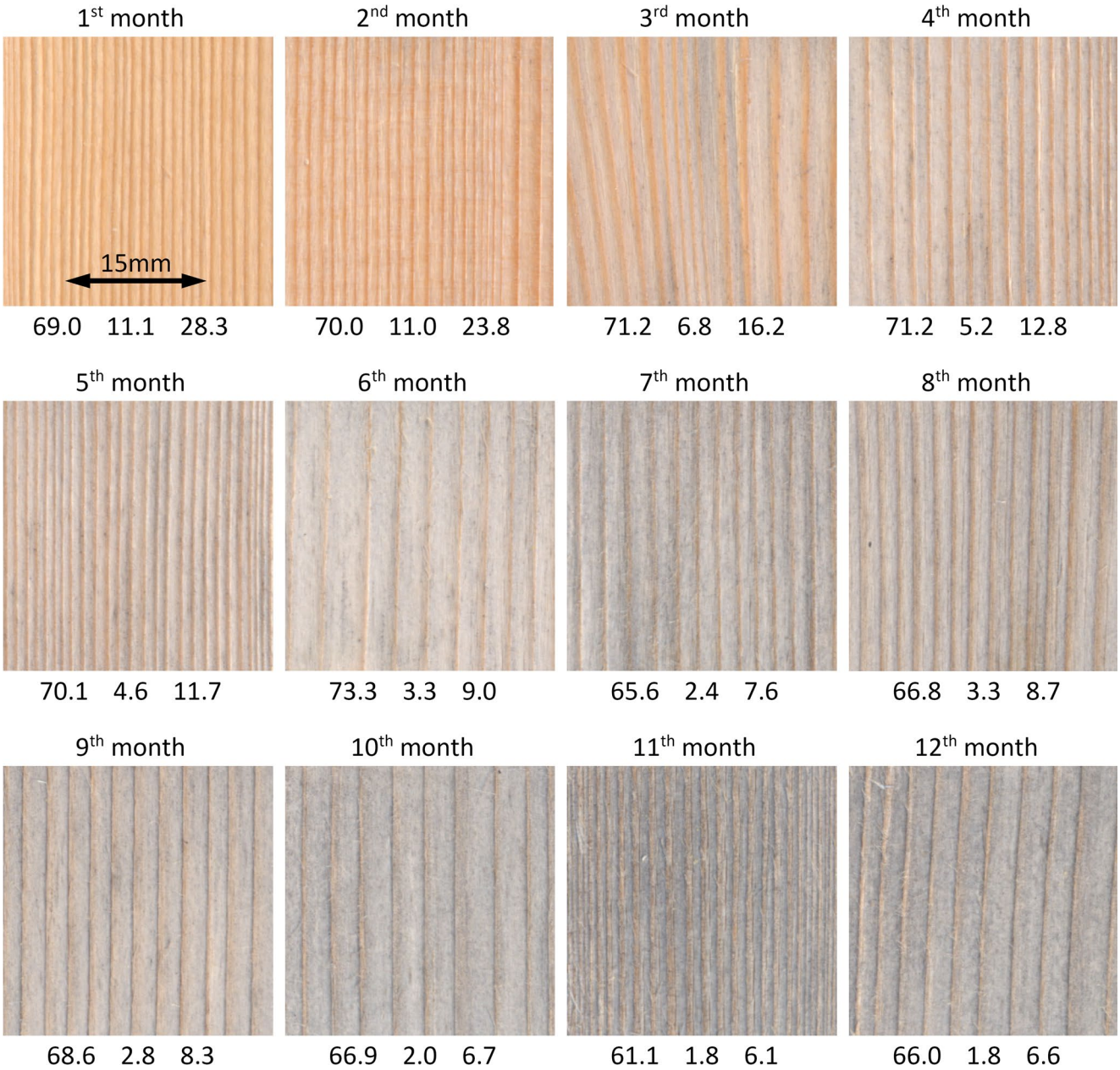


Fig. 7 Example of the appearance changes in wood samples exposed to natural weathering in the UK (location #22)

Interestingly, despite these differences in ΔE magnitude, the final *CIE a* and *CIE b* values were similar across most locations (except the algae-affected location #12 (Poznan)). This suggests that the *CIE L* component (lightness) is the primary driver of final colour appearance extent, and therefore the main indicator of greying intensity.

The rate and extent of colour change varied substantially between exposure sites. Although all samples showed increasing ΔE values that gradually approached stabilization, the point at which this stabilization occurred differed by location. This variation reflects differences in climatic intensity, such as solar radiation, humidity, precipitation, and temperature cycling, which collectively influence the speed of wood weathering (Eylem et al. 2018). For improved interpretation, the exposure sites were grouped into broader climate categories (temperate, continental, and Mediterranean), reflecting regional climatic behaviour rather than strict Köppen-Geiger classification. This grouping highlights systematic differences in weathering kinetics, with Mediterranean sites generally exhibiting faster colour change due to higher solar radiation, while temperate and maritime climates showed slower and more moisture-driven weathering patterns. To further interpret these differences in a quantitative climate context, the observed variation in

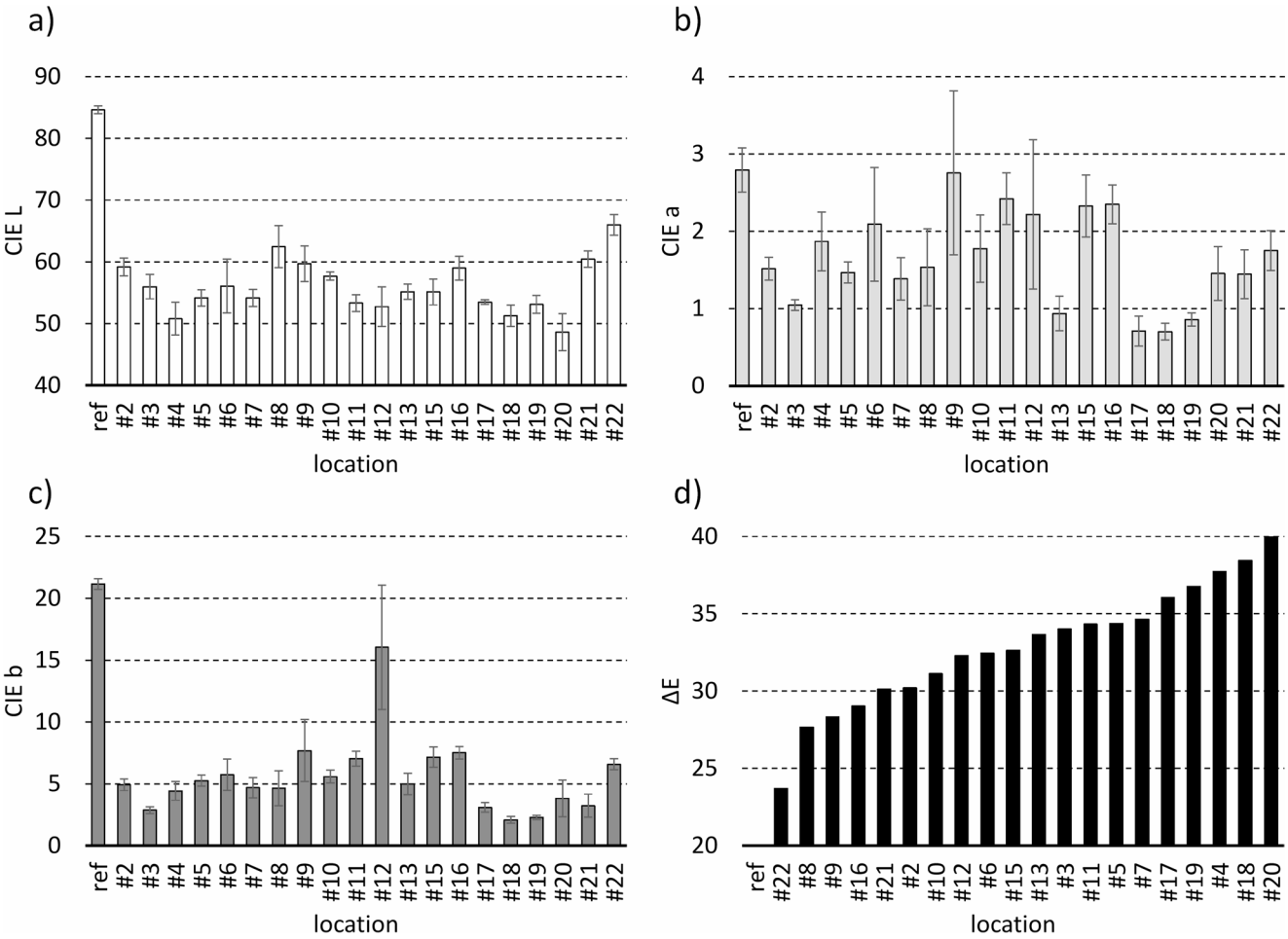


Fig. 8 Individual CIE colour components L **a**, a **b**, b **c** and total colour difference ΔE (d) for samples weathered for one year at different locations. Note: error bars corresponds to the standard deviation of measured values

colour change can be related to climate severity expressed by the Scheffer Climate Index (SCI). Higher SCI values, indicating more favourable conditions for biological activity and moisture-induced degradation, generally corresponded to faster overall colour change and earlier onset of greying (e.g., location #20 in Turkey). In contrast, lower SCI values were associated with slower colour evolution. In addition to SCI as an integrative descriptor, the results also reflect two dominant environmental drivers: (i) UV radiation, which governs lignin photodegradation and the initial increase in chromophoric groups, and (ii) surface moisture availability and wet-dry cycling, which promote leaching processes and biological colonisation. Although the present study does not allow these effects to be isolated directly, their interaction may contribute to the site-dependent differences observed in both the rate and trajectory of colour change across the exposure locations. Moreover, the use of relatively thin specimens, as implemented in this research, should not be interpreted as promoting decay directly. Biological degradation of wood is primarily controlled by moisture availability, moisture fluctuations, and the duration of conditions favourable for microbial activity. Nevertheless, specimens with a smaller cross-section may respond more rapidly to environmental changes because of their higher surface-to-volume ratio, resulting in faster wetting and drying cycles and a greater sensitivity to weathering-related processes occurring at the exposed surface.

A clear contrast is observed between samples from locations #22 (UK) and #20 (Turkey). After 12 months, the UK samples exhibited the smallest overall colour change, whereas the Turkish samples showed the greatest. This outcome is consistent with expected climatic effects: higher UV exposure and more pronounced dry-wet cycling in Turkey promote faster surface degradation compared with the cooler, more humid, and cloudier conditions in the UK. More specifically, the results indicate that colour evolution is governed by two partially competing mechanisms depending on climatic conditions. In climates with high solar radiation, UV-driven photodegradation of lignin dominates the early-stage colour change, leading to rapid formation of

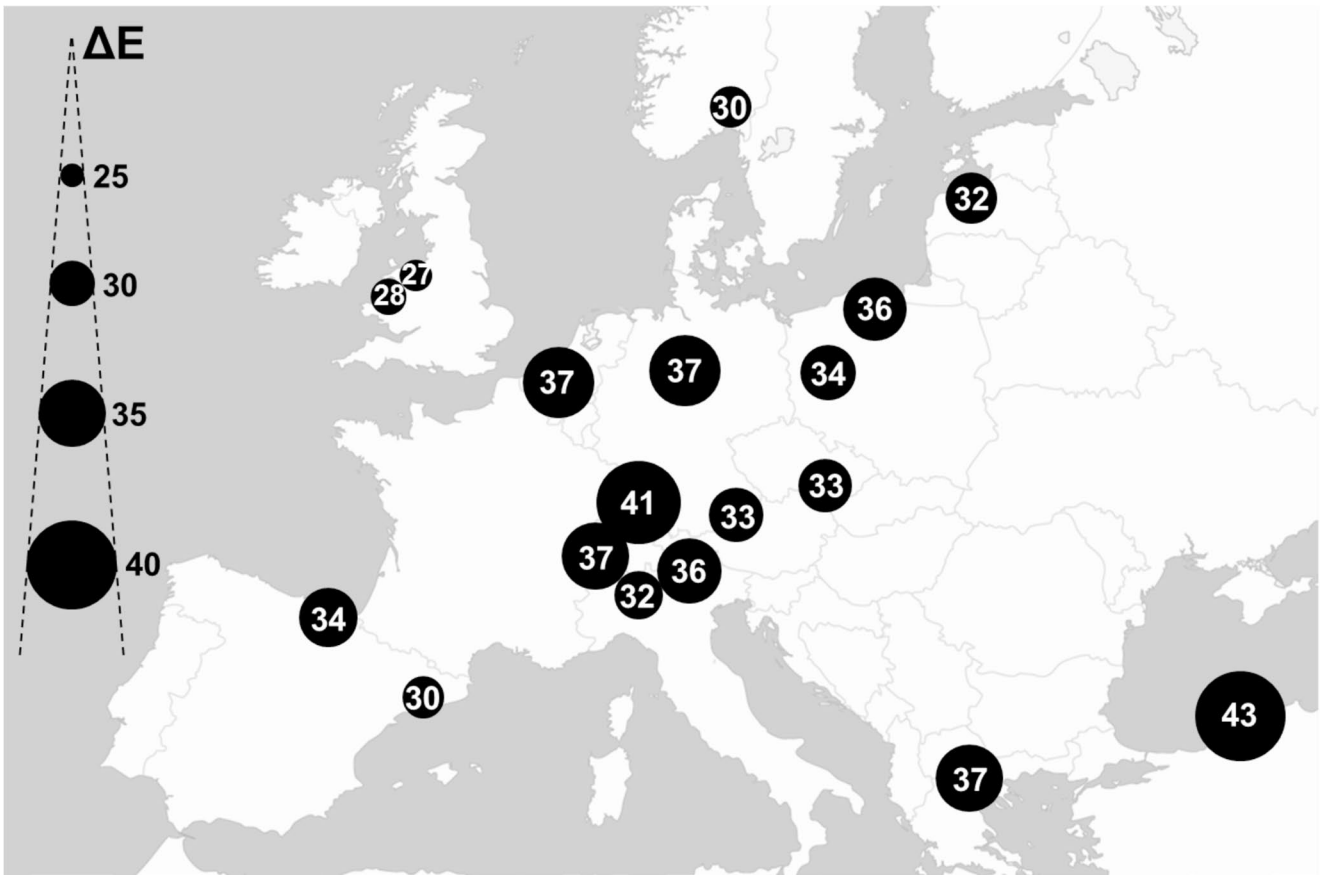


Fig. 9 Change of CIE Lab colour (ΔE) of samples exposed for one year to natural weathering at different locations in Europe. Note: number in the circle indicates the recorded ΔE value

chromophoric compounds and pronounced lightness reduction. In contrast, in humid and moisture-rich environments, prolonged surface wetness may lead to increased relevance of biological activity, particularly fungal colonisation and blue stain development, which contribute to darker discoloration and increased variability in CIE b* values. These both mechanisms act in parallel but with different intensities depending on local climatic conditions, resulting in the observed divergence in both the kinetics and magnitude of colour change between sites.

A geographical overview of the ΔE values from the Round Robin experiment is presented in Fig. 9. Although the map does not reveal distinct spatial clustering, it clearly demonstrates that, while the fundamental mechanisms of natural wood weathering appear consistent across sites, the kinetics of these processes differ. This is logically explained by the varying intensity and combination of weather factors at each location. Such interpretation is supported by literature, which shows that colour changes in unprotected wood are strongly influenced by climate. Studies conducted within the same climate zones report comparable trends in colour development, such as similar CIE Lab values observed in humid subtropical environments, as well as consistent lightness decrease and surface darkening in boreal climates, often associated with fungal growth. These findings confirm that, although weathering mechanisms are universal, their rate and visual manifestation are largely governed by site-specific environmental conditions (Lie et al. 2019).

In addition to climatic drivers, local biological activity may have contributed to site-specific deviations in colour change, particularly during the early exposure phase. The development of moulds, blue-stain fungi, and surface-colonising microorganisms is strongly influenced not only by regional climate but also by microenvironmental conditions such as surrounding vegetation, shading, airflow, and proximity to built structures. These factors were not explicitly quantified in the present study, but may help explain certain site-specific observations, such as relatively elevated ΔE values at locations like Biel compared with other continental sites. Consequently, part of the observed variability between sites may be attributed to differences in local biological colonisation dynamics in addition to climatic influences.

At the same time, it is acknowledged that microclimatic conditions such as mounting height above ground, local airflow, and proximity to surrounding structures may influence absolute weathering rates. In the present study, exposure

racks were installed according to the infrastructure available at each site (including both ground-based and elevated installations), while maintaining identical specimen orientation and spacing within each exposure system. Although the distance from ground level was not fully uniform across all locations, the experimental design ensured that all samples within a given site experienced identical local exposure conditions. Consequently, the focus of the study is on relative differences between climatic regions rather than absolute site-to-site equivalence of microenvironmental parameters. This harmonised within-site setup allows robust comparison of climate-driven trends despite unavoidable variations in local installation geometry. It should also be noted that the present study does not include direct measurements of site-specific UV dose, surface wetness duration, or detailed quantification of fungal colonisation. Consequently, the observed colour changes represent an integrated response to combined environmental drivers rather than isolated mechanistic contributions. In particular, interactions between short-term UV exposure and transient surface moisture conditions, which are known to strongly influence photodegradation and biological activity, cannot be resolved using aggregated climate descriptors alone. Therefore, the results are not intended to support mechanistic attribution or predictive modelling of individual degradation pathways, but rather to provide harmonised, comparative field evidence of climate-dependent weathering behaviour across European exposure sites.

Recent studies on natural weathering of wood have increasingly emphasised the need to integrate surface appearance changes with climatic descriptors and multifactor environmental exposure models. In particular, recent work has highlighted the combined influence of radiation intensity, moisture dynamics, and biological colonisation in governing early-stage surface degradation, reinforcing the view that colour change cannot be attributed to a single dominant mechanism (Niklewski et, al, 2022). Compared with these recent developments, the present study contributes by providing harmonised multi-site experimental evidence under controlled exposure conditions, enabling direct comparison of climate-driven trends across geographically distinct locations.

The interpretation of results obtained after one year of natural exposure should also be considered with caution when assessing long-term weathering behaviour. The first year of exposure is typically characterised by rapid photochemical changes, including lignin degradation and the formation and removal of chromophoric compounds, which contribute substantially to the observed colour change. As weathering progresses, however, surface erosion, biological colonisation, and the gradual depletion of readily photodegradable components alter the dominant mechanisms governing colour development. Consequently, the relationships observed during the initial exposure period may not remain same over time, and the magnitude as well as the rate of colour change may evolve differently during subsequent years. Although beyond the scope of the present report, the collected dataset forms a solid foundation for developing a dose-response model linking colour change dynamics to location-specific climatic parameters. The results presented here describe the response component of the model, whereas the relationship between colour change and climatic exposure variables will be examined in a subsequent publication.

5 Conclusion

This study demonstrated that Norway spruce undergoes rapid and pronounced colour changes during natural weathering, with the most substantial alterations occurring within the first month of exposure. After this initial phase, the progression of colour change slowed and, in most cases, approached a stable trend toward the end of the 12-month period.

The analysis of the *CIE Lab* colour components revealed a characteristic two-stage behaviour. The early phase was marked by temporary colour enrichment, reflected in increasing *CIE a* and *CIE b* values, followed by a second stage dominated by decolouration and greying, primarily expressed through reductions in *CIE L*. These findings confirm that lightness is the most sensitive indicator of surface degradation and the primary contributor to the total colour difference ΔE.

Climatic conditions played a decisive role in the kinetics of weathering. Although the underlying mechanisms of photodegradation were consistent across all sites, the rate and extent of colour change varied substantially between locations. Local microenvironmental conditions, including potential biological colonisation influenced by site surroundings, may also have contributed to site-specific deviations in colour change and should be considered in the interpretation of multi-site weathering data.

The geographical comparison of ΔE values confirmed that no simple clustering pattern exists across Europe; however, the diversity of weathering rates highlights the need to consider location-specific climatic influences when assessing material durability. The dataset generated through this Round Robin experiment provides a valuable foundation for modelling dose-response relationships between environmental conditions and surface appearance changes. The present work represents the "response" component of such a model, which will be presented as a follow-up of this study.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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