



Extreme drought stress provides an ecological benchmark for high-resolution available water capacity maps of Swiss forest soils

Colin K. Bloom¹, Katrin Meusburger^{1,2}, Lorenz Walthert¹, Andri Baltensweiler¹

¹Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, 8903, Switzerland

5 ²Department of Environmental Systems Science, ETH Zurich, Zürich, 8092, Switzerland

Correspondence to: Colin K. Bloom (colin.bloom@wsl.ch)

Abstract. Available water capacity (AWC) is a fundamental soil hydraulic property controlling plant water supply and drought response, yet existing AWC estimates for Switzerland's forests are an order of magnitude coarser than the scale of an individual tree's root system. Here we produce 25 m resolution maps of mineral soil AWC for Switzerland's forest soils using ten
10 published pedotransfer functions (PTFs) applied to a common set of gridded 25 m digital soil maps. We introduce a novel method for evaluating these PTF-derived AWC estimates using early leaf discoloration, an indicator of extreme drought stress, in European beech (*Fagus sylvatica* L.). Performance of single feature logistic regression models, using estimated AWC as a predictive feature and September 2018 early leaf discoloration as a target, varied substantially by PTF (ROC-AUC between 0.42 and 0.63). The strongest relationships between AWC and discoloration showed a negative trend and relatively strong
15 model calibration (R^2 up to 0.82). Combining AWC with total 2018 summer precipitation and maximum 2018 summer temperature had little impact on model discrimination, but improved model calibration (R^2 up to 0.90) in late summer 2018 with discoloration proportions of nearly 80% at the most susceptible sites. Averaging the results of the four comparatively best-performing PTFs in these models produced two 25 m soil AWC products for the Swiss forest (mean 1 m and 2 m depth AWC) with uncertainty estimates based on variation among PTFs ($\pm 1\sigma$). While both the mapped AWC values and the relative
20 performance of individual PTFs remain dependent on soil properties of the underlying digital soil maps, these new AWC estimates are immediately applicable to forest drought monitoring and species distribution, ecohydrological, and land-surface modelling.

1 Introduction

Soil hydraulic properties govern the storage and movement of water in the vadose zone and are among the most influential
25 parameters in hydrological, ecohydrological and land-surface models (Wankmüller et al., 2024). These properties control infiltration, drainage, plant water availability and energy exchange between the land surface and atmosphere, yet remain among the most difficult soil characteristics to measure and estimate across large spatial scales (Assouline and Or, 2013; Gupta et al., 2022). Among many soil hydraulic properties, available water capacity (AWC), which represents the volume of water held in the soil between its field capacity (the point at which excess water has drained away under gravity) and the permanent wilting



point (where remaining water is held too tightly by soil particles for roots to extract; Cousin et al., 2022), stands out as a key determinant of plant water availability and, ultimately, forest response to drought (Klesse et al., 2022; Meusburger et al., 2022). For example, during the hot and dry summer of 2018, many of Central Europe's beech (*Fagus sylvatica* L.) forests exhibited signs of drought stress including early leaf discoloration (Fig. 1), wilting, and reduced growth (Schuldt et al., 2020; Brun et al., 2020; Klesse et al., 2022; Bloom et al., 2026). By the end of August 2018, some trees were heavily stressed while other nearby trees showed few signs of the hot and dry conditions. This variability in drought stress occurred at both regional and local scales (Brun et al., 2020; Bloom et al., 2026). Brun et al. (2020) attributed regional variability in 2018 drought stress to meteorological conditions and local variability to a combination of plant specific traits and local site conditions. Klesse et al. (2022) showed that local AWC and tree height had a large influence on individual tree growth variability and Meusburger et al. (2022) demonstrated that regional patterns of early leaf discoloration were strongly modulated by soil matric potential, or the force with which water is held by soil particles – a combined result of AWC, soil moistening from precipitation, and evapotranspiration forced by atmospheric demand.

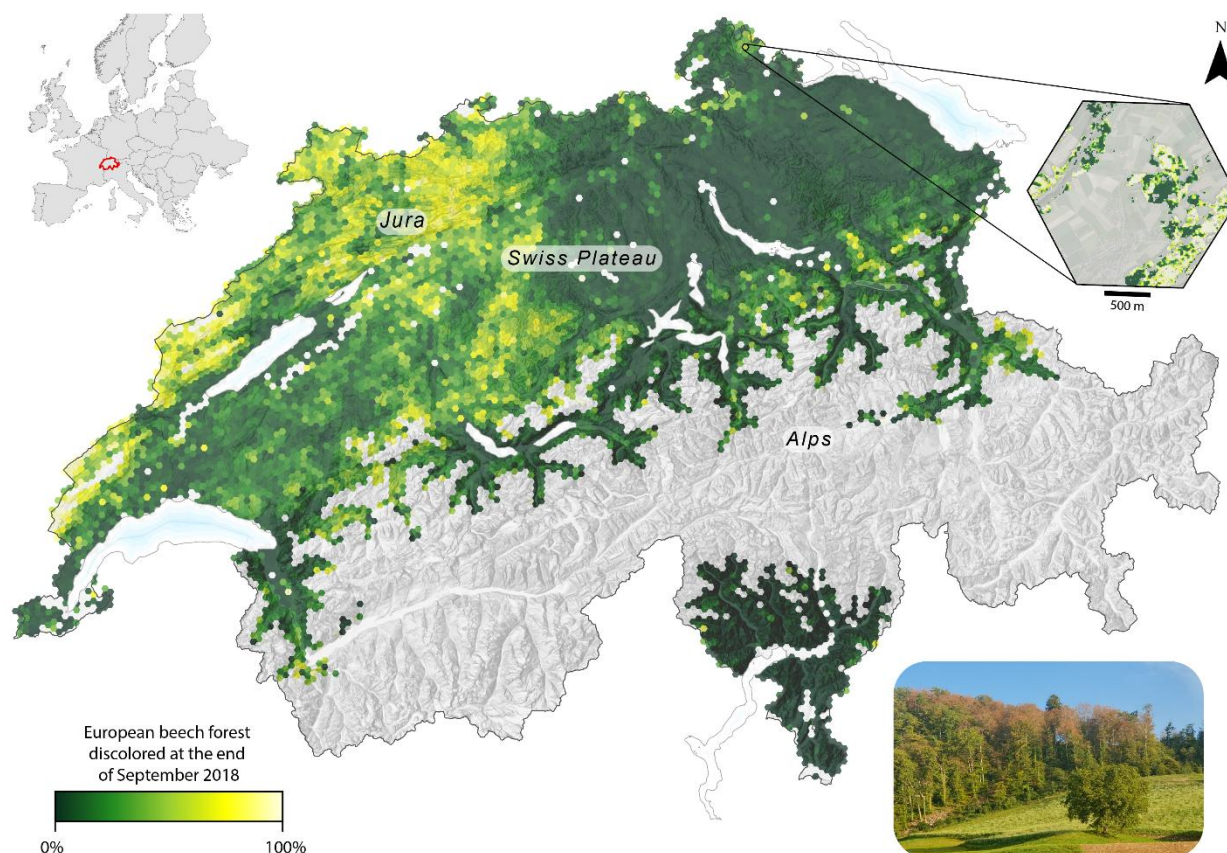


Fig. 1: Percent of European beech dominated forest discolored at the end of September 2018 (Bloom et al., 2026) within 3 km² aggregated hexagons for visualization alongside an example of the native 10 m resolution early leaf discoloration probability (0: Dark Green to 1: Yellow; Bloom et al., 2026) for a single hexagon, a location overview, and an example photo of early leaf discoloration in the field (Image: L. Walthert). The national basemap is a hill shade derived from swissALTI3D (swisstopo, 2024a) and the hexagon basemap is an extract from SWISSIMAGE (swisstopo, 2024b).



Using tension within their tissues, plants must lower their internal water potential below soil matric potential to draw water from the soil into the roots. Under drought conditions with low water supply, high tension can pull air into the plant's water conducting tissues resulting in xylem embolism (Sperry and Tyree, 1988) which further reduces the flow of water and nutrients throughout the plant (Hacke and Sperry, 2001). Local field investigations by Walthert et al. (2021) demonstrated that shallow soil with low AWC and low soil matric potential promoted stress in individual European beech trees during the 2018 drought resulting in high rates of xylem embolism and early leaf discoloration. These observations add to a continuously growing body of evidence that consistent and sufficient access to soil water lowers plant stress under hot and dry meteorological conditions (e.g., Bréda et al., 2006; Carminati and Javaux, 2020; Hammond et al., 2022; Kahmen et al., 2022; Werner et al., 2025). Despite evidence that soil water availability controls drought stress at both the individual tree and regional scale, quantifying AWC at any given location remains a fundamental challenge. AWC is influenced by a range of soil properties including texture, organic matter content, bulk density, and rooting depth all of which are often spatially heterogeneous in forest soils (Teepe et al., 2003). Soil heterogeneity may help to explain why neighbouring trees of the same species and stature react so differently under nearly identical meteorological conditions, but it also severely limits accurate characterization of AWC over large areas. In-situ AWC measurements require expensive and time-consuming sampling and laboratory analysis. Because comprehensive fine-scale sampling is rarely feasible over large areas, AWC is often estimated at coarser, spatially averaged resolutions. Such generalization can obscure local differences in water availability that are important for characterizing drought stress. The roots of individual mature European beech trees, for instance, typically take up water within less than a 20 m radius of the tree stem (Meinen et al., 2009). Most regional efforts to approximate AWC, including those used to create existing 500 m resolution AWC maps for the Swiss forest (Meusburger et al., 2022), rely on a combination of digital soil maps and pedotransfer functions (PTFs; Cousin et al., 2022). PTFs are widely used to estimate soil hydraulic properties from readily available soil information such as texture, organic matter content and bulk density. They leverage estimates of soil texture, profile characteristics, and laboratory values from a finite number of observations to empirically generalize the parameters of the soil water retention curve, and thereby derive AWC, across sites. In theory, these methods should enable effective upscaling of AWC, but numerous PTFs are available for European soils and there are few practical tools to assess their relative performance under unseen conditions, absent laboratory testing (Schoch et al., 2025). Here, we re-examine AWC in Switzerland's forests at the native 25 m resolution of existing high-resolution digital soil maps (Baltensweiler et al., 2021). To address one of the major bottlenecks in predicting soil hydraulic properties at landscape scale, we evaluate different pedotransfer function estimates of AWC using observed tree-level drought response during the extreme 2018 drought as an independent field-based benchmark for PTF performance. Beyond introducing a novel test of PTF effectiveness, the results provide a window into site specific drought susceptibility and AWC maps which approach the spatial scale of individual tree water uptake. The results have broad and direct application, from improving drought vulnerability assessment and water balance modelling to refining predictors incorporated into species distribution models under future climate scenarios.

2 Data and Methods

2.1 Overview

To estimate available water capacity (AWC) across Switzerland's forest soils, we selected ten common PTF functions (Table 1) and applied each independently to the 25 m gridded digital soil maps of Baltensweiler et al. (2021). Profile AWC was calculated by integrating soil layers to depths up to 1 and 2 meters. We compared the distributions of these AWC estimates and intersected each with satellite remote sensing derived European beech early leaf discoloration classifications developed by Bloom et al. (2026), effectively dividing the datasets into "discolored" and "not discolored" subsets. To identify the most applicable PTFs for Swiss forest conditions, we analytically examined the proportion of discolored pixels within different ranges of AWC and quantitatively trained logistic regression classifiers of discoloration using each AWC estimate individually and in combination with seasonal temperature and precipitation.

Table 1. Details of the 10 pedotransfer functions (PTFs) used in this analysis. Abbreviations are as follows, MvG: Mualem–van Genuchten, SOC: Soil Organic Carbon, OM: Organic Matter Content, BD: Bulk Density, FC: Field Capacity, PWP: Permanent Wilting Point.

Author	Shorthand	Predicted	Approach	Texture	SOC	BD	Notes	FC kPa matric potential head	PWP kPa matric potential head	PWP/FC Defined?
Wessolek et al., 2009	Wessolek	MvG Parameters	Texture Classification	TRUE	FALSE	FALSE		-33	-1600	TRUE
Wösten et al., 1999	Wösten	MvG Parameters	Regression	TRUE	TRUE	TRUE	Topsoil Flag and van Bemmelen SOC% to OM%	-33	-1600	TRUE
Teepe et al., 2003	Teepe	MvG Parameters	Regression	TRUE	FALSE	TRUE		-33	-1600	TRUE
Puhlmann and von Wilpert, 2011	Puhlmann	MvG Parameters	Regression	TRUE	TRUE	TRUE		-33	-1600	TRUE
Weynants et al., 2009	Weynants	MvG Parameters	Regression	TRUE	TRUE	TRUE		-33	-1600	TRUE
Zhang and Schaap, 2017	Zhang	MvG Parameters	Deep Learning	TRUE	FALSE	TRUE	v3 - arith	-33	-1600	TRUE
Schoch et al., 2025	Schoch	MvG Parameters	Regression	TRUE	TRUE	TRUE		-33	-1600	TRUE
Saxton and Rawls, 2006	Saxton	FC and WP	Regression	TRUE	TRUE	FALSE	van Bemmelen SOC% to OM%	-33	-1500	FALSE
Tóth et al., 2015	Tóth	FC and WP	Regression	TRUE	TRUE	FALSE		-33	-1585	FALSE
Szabó et al., 2021	Szabó	FC and WP	Random Forest	TRUE	TRUE	FALSE	PTF02	-33	-1500	FALSE

2.2 Data

2.2.1 Digital soil maps

The 25 m gridded digital soil maps of Baltensweiler et al. (2021) were derived from random forest models trained on 2,071 forest soil profiles across Switzerland. These maps provide spatial estimates for soil texture (clay, sand, and gravel fractions), soil organic carbon content (SOC), and fine earth bulk density (BD) across six standard depth intervals: 0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, 60–100 cm, and 100–200 cm. These variables represent the primary soil properties required as inputs for the selected pedotransfer functions. Prediction performance varied by soil property, yielding R^2 values between 0.21 and 0.49 (Baltensweiler et al., 2021). The digital soil maps were used as the common input dataset for all PTFs, ensuring that differences among AWC estimates were solely attributable to the pedotransfer functions themselves.



105 2.2.2 Early leaf discoloration

Bloom et al. (2026) used field observations of European beech early leaf discoloration and five vegetation indices derived from Sentinel-2 satellite data to train a Support Vector Classifier differentiating discolored and non-discolored 10 m pixels across Switzerland's beech-dominated forests. This model was used to predict probability of canopy discoloration at 5-day intervals from June to September 2017 to 2023, achieving an F1 score of 0.85 using an optimized 40% probability classification threshold. We spatially resampled discoloration estimates at the end of June, July, August, and September using a mean pixel approach to match the 25 m spatial resolution and extent of the digital soil maps.

2.2.3 Meteorological data

We aggregated 250 m daily gridded precipitation data from Meteotest (2020) to calculate total precipitation (mm) over the winter and spring months (December–May) preceding the 2018 summer drought and during the summer months (June, July, and August) from 2017 to 2022. Likewise, we calculated mean and maximum summer temperature (°C) from the gridded 250 m daily mean air temperature dataset (T) of Meteotest (2020) for the years 2017 to 2022. More specifically, maximum summer temperature represents the hottest daily mean temperature of the summer. Daily vapor pressure deficit (VPD, kPa) was calculated from T and dewpoint temperature (T_d) from Meteotest (2020) as Eq. 1

$$\text{VPD} = e_s(T) - e_s(T_d) \quad (1)$$

120 where saturation vapor pressure (e_s , kPa) was computed using the Tetens formula (Eq. 2; Tetens, 1930; Allen et al., 1998):

$$e_s(T) = 0.6108 \exp \left[\frac{17.27T}{T+237.3} \right] \quad (2)$$

VPD was calculated at a daily resolution before temporal aggregation, and the daily values were then summarised as the summer mean and maximum for each year. Finally, all the aggregated meteorological datasets were resampled to match the extent and resolution of the 25 m soil grids using a nearest-neighbour approach.

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2.3 Methods

2.3.1 Pedotransfer functions

We selected a representative set of commonly used PTFs for global and European soils (Table 1) based on recent use in previous studies of AWC in the Swiss forest (e.g., Meusburger et al., 2022; Schoch et al., 2025) and to capture a diversity of methodologies. The selected PTFs fall roughly into three methodological categories. The first two categories estimate Mualem–van Genuchten (MvG; Mualem, 1976; van Genuchten, 1980) parameters of the soil water retention curve to calculate volumetric water content at field capacity (FC) and permanent wilting point (PWP). The MvG parametrization is further broken into classification and regression approaches. In the classification approach (Wessolek et al., 2009), MvG parameters are assigned directly to discrete soil texture groups. In the regression approach (Wösten et al., 1999; Teepe et al., 2003; Weynants et al., 2009; Puhlmann and von Wilpert, 2011; Zhang and Schaap, 2017; Schoch et al., 2025), MvG parameters are calculated

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from continuous soil texture predictors. In the third category, PTFs are used to estimate FC and PWP (Saxton and Rawls, 2006; Tóth et al., 2015; Szabó et al., 2021) directly via empirical equations without full water retention curve parameterization. The majority of the applied PTFs are based on multiple regression functions (Wösten et al., 1999; Teepe et al., 2003; Saxton and Rawls, 2006; Weynants et al., 2009; Puhlmann and von Wilpert, 2011; Tóth et al., 2015; Schoch et al., 2025). However, the PTF of Zhang and Schaap (2017) uses a deep learning approach and the PTF of Szabó et al. (2021) uses a random forest approach.

Each PTF application followed a similar workflow. Soil texture, including sand and clay fraction, SOC, and BD, was extracted from the associated gridded soil layer in the digital soil maps. Silt fraction was calculated as 1 minus the sum of the clay and sand fractions. We applied PTFs to each depth layer and pixel independently. For the MvG classification approach, soils were grouped into appropriate texture classes and assigned MvG parameters. For the other two approaches, texture was applied directly to PTF equations to predict MvG parameters and/or FC and PWP. Where specific PTF equations required soil organic matter (SOM) content rather than SOC (Saxton and Rawls, 2006; Wösten et al., 1999), we converted the values using the conventional (although conservative) van Bemmelen factor (Eq. 3; van Bemmelen, 1890; Pribyl, 2010):

$$SOM (\%) = SOC (\%) \times 1.724 \quad (3)$$

For all MvG-based PTFs, FC was defined at a matric potential of -33 kPa (Tóth et al., 2015) and PWP at $-1,600 \text{ kPa}$ (Richards and Weaver, 1943). We were more limited in our ability to define matric potential thresholds for direct FC/PWP equations. Saxton and Rawls (2006) and Szabó et al. (2021) defined FC at a matric potential of -33 kPa and PWP at $-1,500 \text{ kPa}$ while Tóth et al. (2015) defined FC at a matric potential of -33 kPa and PWP at $-1,584.8 \text{ kPa}$. In all cases, fine-soil AWC was calculated as the difference between water content at FC and PWP. To determine the total AWC of a given depth layer, the fine-soil AWC was multiplied by the horizon thickness and the fine-earth proportion ($1 - \text{gravel content}$). For this regional assessment, gravel content was assumed to be non-porous. Total AWC for 1 m and 2 m depth layers was calculated as the cumulative sum of the individual soil layers down to the respective target depth.

For the sake of simplicity, we will refer to the different PTF estimates of AWC throughout the remainder of this manuscript by a combination of their methodological origin (the last name of the first author) and aggregated soil depth. For instance, 1 m depth aggregated AWC estimated using the PTF of Wessolek et al. (2009) will be referred to as 1 m AWC_{Wessolek} while the 2 m AWC using the PTF of Puhlmann and von Wilpert (2011) will be referred to as 2 m AWC_{Puhlmann} . A full list of PTFs and associated citations can be found in Table 1.

2.3.2 AWC and early leaf discoloration

We split AWC grids based on their coincidence with the early leaf discoloration maps. This resulted in two categories of AWC in each month, discolored and not discolored at the end of June, July, August, and September 2018 based on a 40% classification threshold for discoloration probability (Bloom et al., 2026). We visually examined these distributions as histograms based on the proportion of early leaf discoloration in 25 equally sized AWC bins across Switzerland with a minimum of 50 pixels per bin.



To quantify the relationship between each PTF's AWC estimate and early leaf discoloration, we applied a nested spatial cross-validation scheme where an outer 10-fold spatial cross-validation (grouping Switzerland's forests into 30 km blocks) provided a held-out prediction for every pixel. Within each outer fold's training data, an inner 5-fold spatial cross-validation was used to tune model hyperparameters, so that no fold used for hyperparameter selection overlapped with the fold on which it was subsequently evaluated. Within each outer fold, we limited the AWC of the training portion to its 0.001–0.999 quantile range to remove outliers, then standardized AWC (zero mean, unit variance) in the training portion and in the held-out portion using the mean and standard deviation of the training portion.

We trained a logistic regression model of early leaf discoloration on each outer fold's training data using AWC as the sole predictive feature. The model's C parameter was tuned within the inner cross-validation using a 20-iteration random search optimizing for ROC-AUC. For each outer fold we evaluated the resulting model on its held-out data using ROC-AUC, PR-AUC, and F1-score at an optimized threshold. We report these metrics as the mean $\pm$ standard deviation across the 10 outer folds.

We also examined model performance and generalizability by pooling the held-out (out-of-fold) predicted probabilities across all 10 outer folds so that every pixel contributed exactly one prediction, from a model that never saw that pixel during training. We grouped these pooled probability predictions into 50 equally spaced bins, calculating the proportion of actual discoloration within each bin. Bins containing fewer than 50 observations were excluded. This grouping served as a calibration test for the model, where R^2 represents how well the predicted probabilities capture the risk of discoloration in each pixel. For example, in a well-calibrated model, 60% of pixels with a discoloration probability around 0.6 should be discolored, while 20% of pixels with a discoloration probability around 0.2 should be discolored.

To better explain variation in the early leaf discoloration–AWC relationship in the absence of full process-based hydrological modelling (e.g., Soil-Vegetation-Atmosphere Transfer, SVAT models), which would otherwise simulate soil water balance directly from climate, soil, and vegetation inputs, we also standardized total precipitation and maximum temperature in the summer months (June, July, and August) of 2018 as proxies for soil water re-filling and high atmospheric demand. Following the same nested spatial cross-validation, standardization, and calibration procedure described above, we trained a model of discoloration using AWC, total precipitation, and maximum temperature as predictors, with hyperparameter tuning, held-out evaluation, and calibration handled identically to the AWC-only model. We also tested models including mean summer temperature and mean and maximum summer VPD. Total winter and spring (December to May) precipitation was greater than any estimated AWC across Switzerland in 2018, so we excluded it from our models.

3 Results

The ten PTFs we applied resulted in substantially different estimates of AWC across Switzerland's forested soils (Fig. 2). Mean AWC across all ten PTFs was c. 105 ± 30 (1σ) mm at 1 m depth and c. 180 ± 50 mm at 2 m depth (Fig. 2). AWC



200 calculated based on the PTF of Wessolek et al. (2009) resulted in the lowest average AWC at both aggregated depths (1 m and 2 m) while the PTF of Zhang and Schaap (2017) resulted in the highest average AWC (Fig. 2).

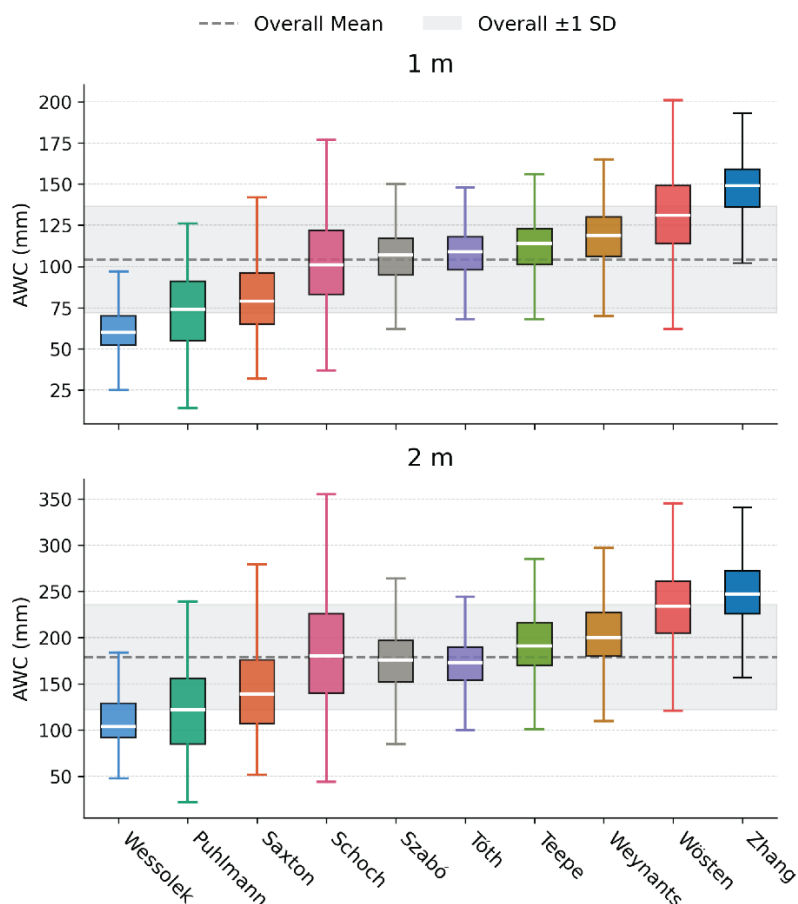


Fig. 2. Box and whisker plots for each PTF at 1 m and 2 m aggregated depths with average AWC $\pm 1\sigma$ in grey. PTF names correspond to the last name of the first author. See Table 1 for additional information.

205 3.1 The AWC-Discoloration relationship

The proportion of European beech dominated forest with early leaf discoloration (shortened to discoloration throughout the remainder of the manuscript) increased dramatically over the summer months of 2018. Proportions of discoloration in 2 m AWC bins were less than 1% in June 2018 and increased to as high as $32 \pm 22\%$ by September (Fig. 3). Although there was a high variance across PTFs, average values generally showed higher discoloration proportions in lower AWC soils and lower discoloration proportions in higher AWC soils at 1 and 2 m aggregated soil depths. We would intuitively expect such a negative relationship as soils with a higher AWC should buffer drought stress resulting in less discoloration.

210 The remainder of our presented analysis focuses on discoloration at the end of September 2018. The months of June and July present relatively low proportions of discoloration (Fig. 3), representing a relatively minor 0.2% and 1.07% of classified

European beech forest area respectively. Comparatively, later-season early leaf discoloration in August and September
 215 accounts for 5.5% and 21.3% of forested areas, respectively. Our analysis focuses on September as it captures the greatest
 cumulative drought stress of the growing season, providing a high-contrast signal where the relationship between soil AWC
 and discoloration proportion is most pronounced.

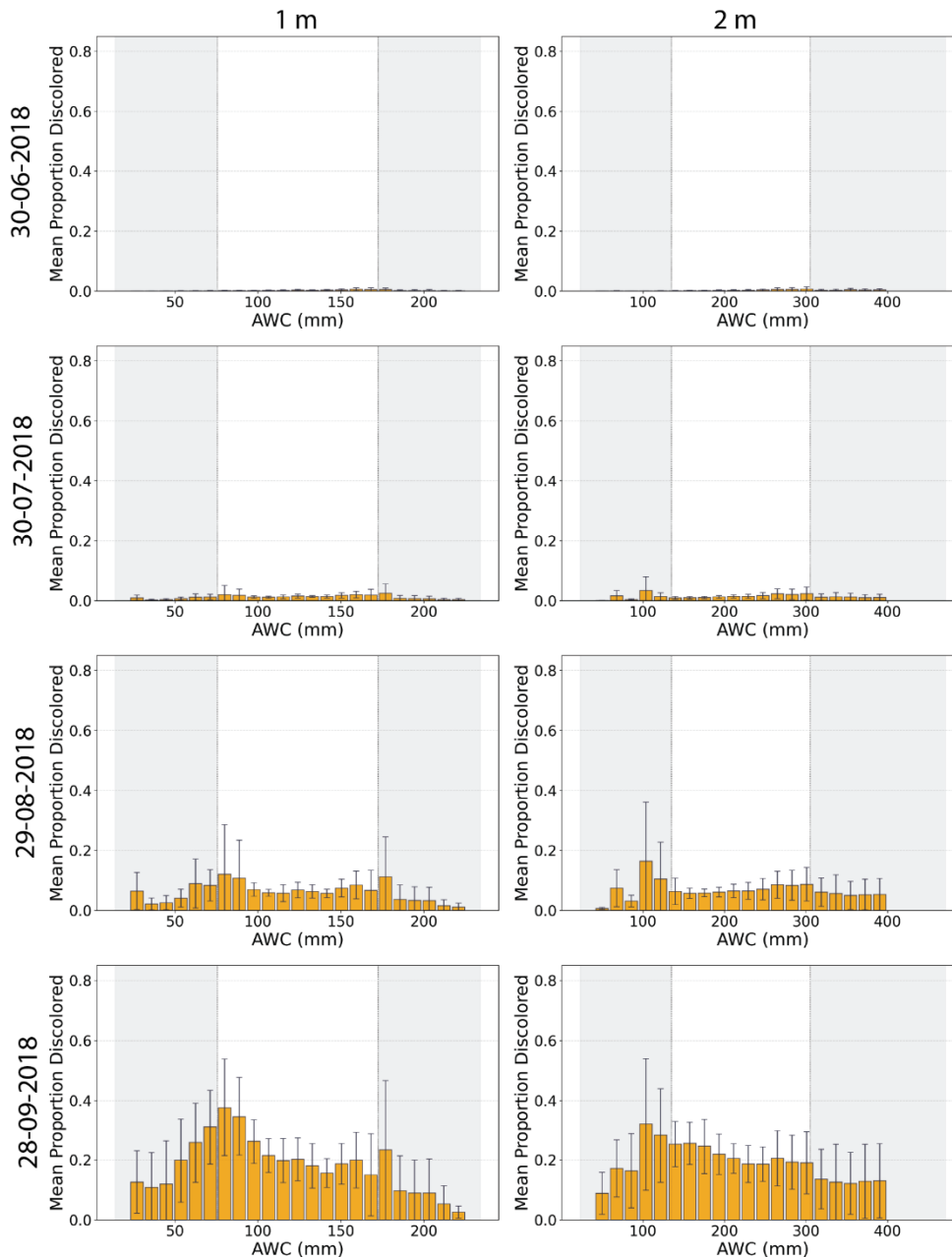


Fig. 3. Discoloration proportion in equal size bins of AWC based on an average of all ten PTFs. Grey areas represent high and low quartile ranges.



Individually examining each AWC estimate revealed strong deviations between PTFs (Fig. 4). At 1 m aggregated depths, we observed an intuitive negative relationship between discoloration proportion and AWC in 7 out of 10 PTFs (Fig. 4). In these cases, higher AWC soils were associated with less discoloration. The strongest negative relationships were observed in 1 m AWC_{Teepe} and 1 m AWC_{Zhang} (Fig. 4) where discoloration proportion was as high as 45% and 78% in the lowest AWC soils respectively. AWC_{Schoch} showed a strong positive relationship between AWC and discoloration proportion where higher discoloration proportion occurred at higher estimated AWC soils (Fig. 4). AWC_{Puhlmann} and AWC_{Saxton} showed more subdued trends. In some cases, for example, for AWC_{Toth} and AWC_{Weynants}, we observed two peaks in discoloration proportion, a larger peak in lower (but not the lowest) AWC soils and a smaller peak in higher AWC soils (Fig. 4).

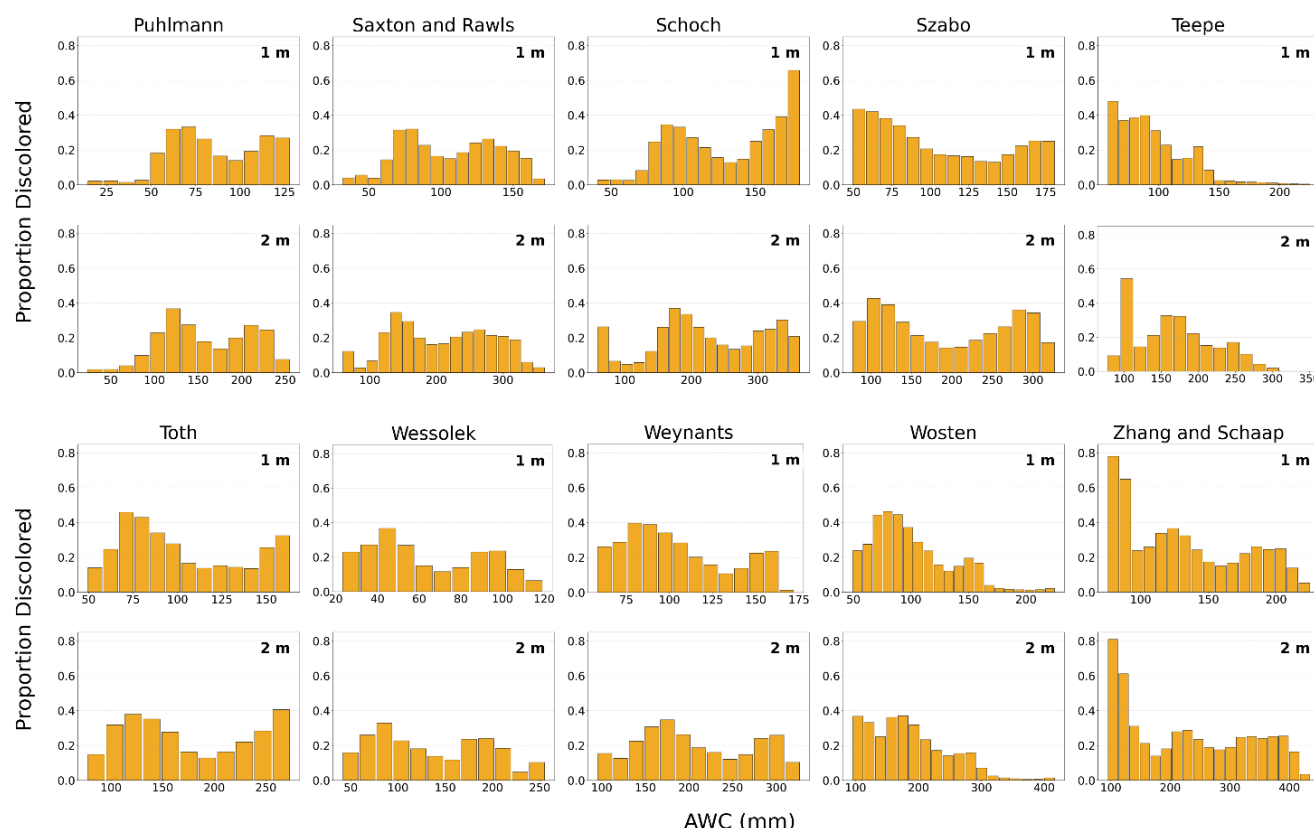


Fig. 4. Discoloration proportion based on bins of individual PTF AWC estimates.

At 2 m aggregated depths, we observed a more variable relationship. AWC_{Wosten}, AWC_{Zhang}, and to a lesser extent AWC_{Teepe}, continued to show a negative relationship while the majority of AWC estimates formed a weak bimodal distribution where higher discoloration proportions were found in both high and low AWC soils.

Logistic regression models of discoloration using AWC as a sole predictive feature (Fig. 5) resulted in variable model performance across PTFs at both 1 m and 2 m depths (Table S1). ROC-AUC ranged from 0.42 ± 0.1 (worse than random) for 2 m AWC_{Saxton} to 0.63 ± 0.11 for 1 m AWC_{Wosten} which had a PR-AUC of 0.32 ± 0.14 , approximately 1.5 times baseline



discoloration prevalence. Optimized F1 scores ranged from 0.31 ± 0.1 for 1 m AWC_{Saxton} to 0.37 ± 0.14 for 1 m AWC_{Wösten} (Table S1).

We observed stronger variability in model calibration R^2 between PTFs (Table 2). Model calibration R^2 fell below zero for 1 m AWC_{Saxton}, AWC_{Schoch}, and AWC_{Puhlmann} and 2 m AWC_{Zhang}, AWC_{Saxton}, AWC_{Schoch}, and AWC_{Puhlmann} (Table 2). This contrasts with relatively strong model calibration for 1 m AWC_{Tóth} (0.68), AWC_{Teepe} (0.74), and AWC_{Wösten} (0.82) as well as 2 m AWC_{Tóth} (0.47), AWC_{Szabó} (0.53), and AWC_{Wösten} (0.79; Table 2).

Table 2. R^2 results for pooled out of fold model calibration using different PTF AWC estimates including AWC_{Wösten} which is presented visually in Fig. 5.

Depth	Puhlmann	Saxton	Schoch	Szabo	Teepe	Toth	Wessolek	Weynants	Wosten	Zhang
1 m	-0.45	-0.66	-0.65	0.62	0.74	0.68	0.30	0.59	0.82	0.39
2 m	-0.27	-0.28	-0.28	0.53	0.36	0.47	0.11	0.22	0.79	-0.98

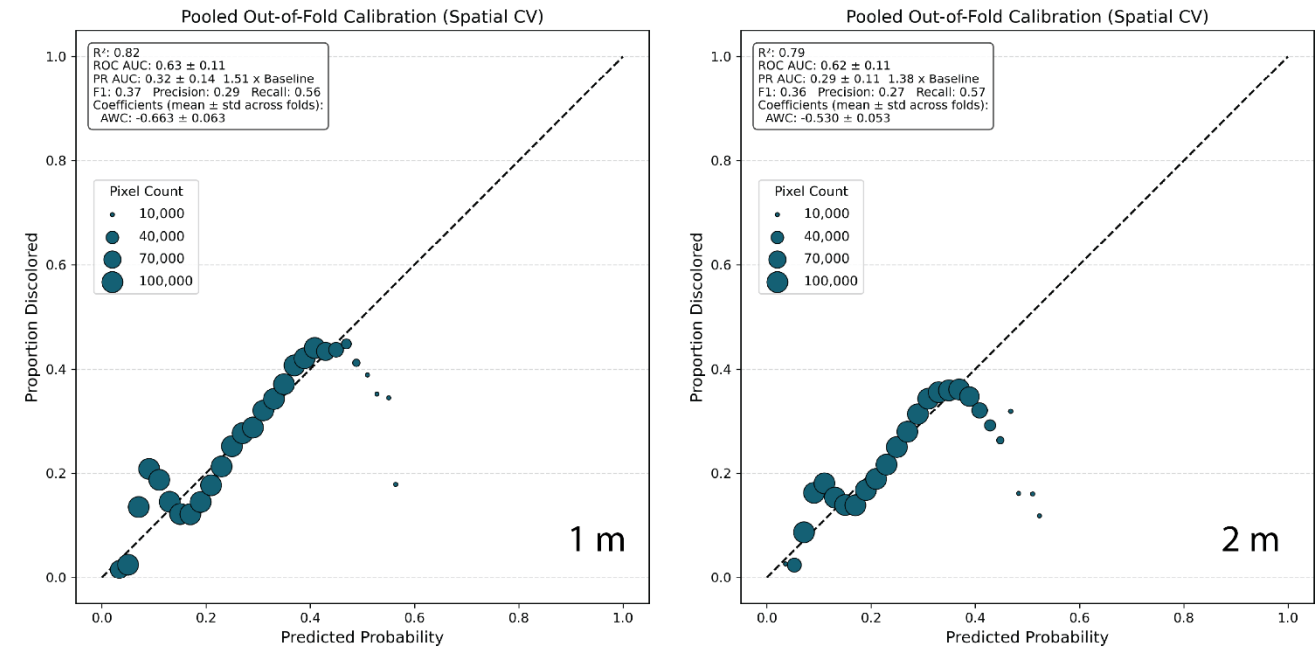


Fig. 5. Example of pooled out-of-fold calibration for logistic regression models relating AWC_{Wösten} at 1 m and 2 m depths to early leaf discoloration.

3.2 AWC and other drought stress predictors

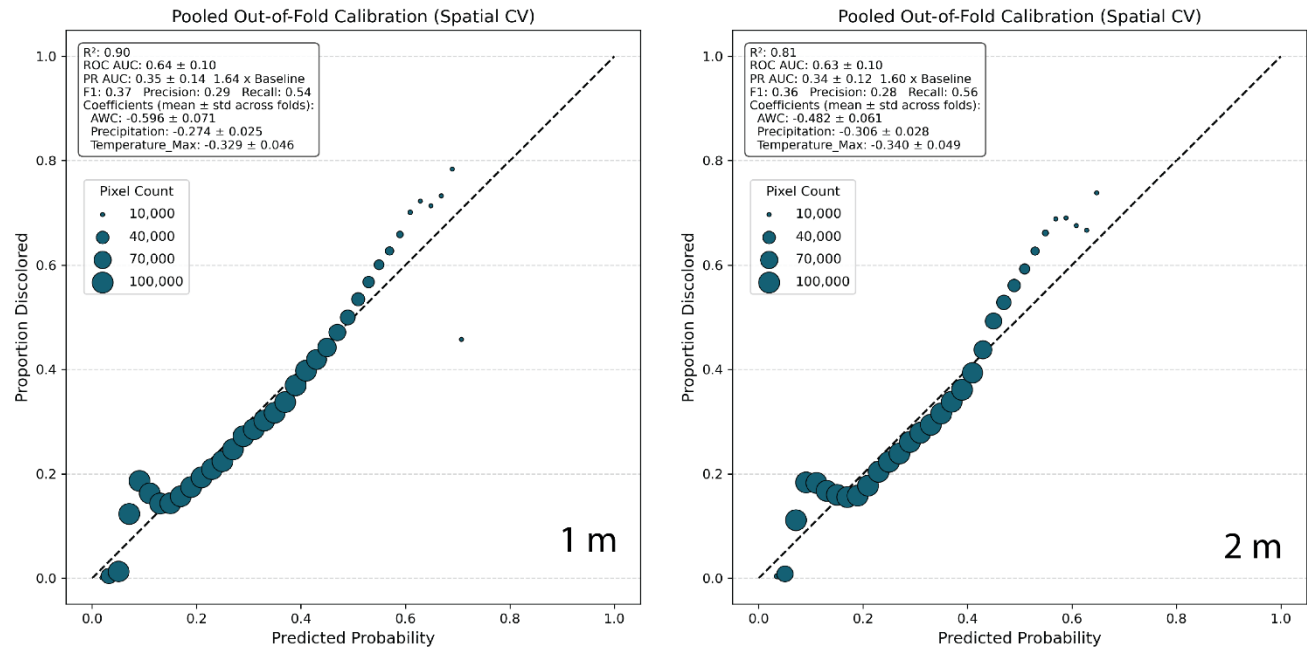
Total discoloration proportions were typically below 45% in the highest individual AWC bins (Fig. 4) but rose to nearly 80% in the most susceptible site combinations when total summer precipitation and maximum summer temperature were introduced alongside AWC as predictive features (Fig. 6). These logistic regression classifications performed only slightly better than classification using individual 1 m and 2 m AWC alone (Table S2) and varied among PTFs with mean ROC-AUC values



255 ranging from 0.60 ± 0.09 to 0.64 ± 0.10 . The best-performing model based on optimized F1-score was 1 m AWC_{Wösten}, with an optimized F1-score of 0.37 ± 0.12 and a PR-AUC of 0.35 ± 0.14 corresponding to c. 1.6 x baseline discoloration prevalence. Calibration R^2 was strong for several models (Table 3) including 1 m AWC_{Wösten} with an R^2 of 0.9 and 1 m AWC_{Teepe}, with an R^2 of 0.87. In most cases, coefficients were negative for all three normalized predictive features, including maximum summer temperature, suggesting a negative relationship with discoloration (Table S2, Fig. 6). As a result of this finding, we examined
260 the influence of replacing maximum summer temperature with mean summer temperature (Table S3), mean summer VPD (Table S4) and maximum summer VPD (Table S5). In each case, the models produced lower performance and still resulted in negative coefficients for temperature and VPD (Table S3, S4 and S5). Across models, variance inflation factor (VIF) analysis revealed only modest correlation between predictors ($VIF < 2$; Tables S2 to S5).

265 **Table 3. R^2 results for pooled out of fold model calibration using different PTF AWC estimates, total summer (June to August) precipitation, and maximum summer temperature. Results are presented visually for AWC_{Wösten} in Fig. 6.**

Depth	Puhlmann	Saxton	Schoch	Szabo	Teepe	Toth	Wessolek	Weynants	Wosten	Zhang
1 m	0.30	0.38	0.25	0.82	0.87	0.83	0.54	0.76	0.90	0.61
2 m	0.41	0.59	0.42	0.69	0.65	0.65	0.31	0.46	0.81	0.32



270 **Fig. 6. Example of pooled out-of-fold calibration for logistic regression models relating total summer precipitation, maximum summer temperature, and AWC_{Wösten} at 1 m and 2 m depths to early leaf discoloration.**



4 Discussion

Assessing AWC is intrinsically difficult and mapping it across the full range of relevant scales, from individual trees to national forests, compounds that challenge. Direct laboratory determination of the water retention curve relies on undisturbed soil cores which are impractical to obtain in the skeleton-rich, stony, soils that characterize much of the Swiss forest. In the absence of direct measurement, AWC must be estimated from more readily mapped soil properties using pedotransfer functions. Yet estimated AWC from different PTFs diverge substantially. Applied to the same gridded soil data across Switzerland's forests, the ten PTFs examined here produced AWC estimates that differed by nearly 150% for a given depth layer (Fig. 2). Until now, there has been no straightforward way to know which PTF offers the most reasonable results across the Swiss forest without extensive sampling and laboratory analysis, and this leaves a fundamental gap: Fine-resolution digital soil maps now exist for the Swiss forest (Baltensweiler et al., 2021), but the hydraulic estimates derived from them cannot be easily verified against ground truth at scale.

This gap is important to fill as AWC-derived products serve varying purposes at different scales. For example, existing 500 m AWC estimates for the Swiss forest (Meusburger et al., 2022) were developed to drive SVAT modelling, for which a 500 m resolution is well matched to the meteorological forcing and computational demands of the approach. Individual-tree drought stress, however, plays out at a much finer spatial scale. Mature European beech trees, for instance, can only take up water within up to 20 m of the stem (Meinen et al., 2009). Resolving AWC at this scale requires both finer soil inputs and a way to test whether resulting estimates are ecologically meaningful. Our application of ten PTFs to 25 m digital soil maps approaches the scale of a tree's individual root water uptake and early leaf discoloration maps from the extreme 2018 drought provide a missing independent and ecologically meaningful benchmark. This allows us to test which fine-resolution AWC estimates actually track tree drought stress across hundreds of thousands of European beech dominated sites.

4.1 Ten unique AWC estimates

Substantial range differences between PTFs applied to the same gridded soil layers (Fig. 2) suggest a strong influence of PTF parameters, weighting and underlying training data on AWC output. For example, the PTF of Wessolek et al. (2009), previously applied to predict AWC across Switzerland at 500 m resolution (Meusburger et al., 2022), produced substantially lower absolute values of AWC as compared to other PTFs in our analysis (Fig. 2). While it does not explain relatively lower values of AWC, the classification approach of Wessolek et al. (2009) is inherently discontinuous meaning that small differences in texture near class boundaries are more susceptible to jumps in AWC. In contrast, regression-based PTFs smooth these jumps but may introduce their own extrapolation risks. For example, Zhang and Schaap (2017) used a deep learning approach and produced much higher AWC values (Fig. 2). PTFs like Teepe et al. (2003), Puhlmann and von Wilpert (2011), and Schoch et al. (2025) were explicitly developed for forest soils, and all incorporate bulk density as a parameter (Table 1). Forest soils tend to have lower bulk density as compared to agricultural soils (Teepe et al., 2003) and this may partially explain higher AWC values from some PTFs. However, neither



the inclusion of bulk density nor the underlying training dataset for the PTF (forest vs. agricultural soil) seem to fully explain the observed range differences between PTFs in this analysis (Fig. 2). For instance, $AWC_{Puhlmann}$, based on forest soil data, had the second lowest average AWC while AWC_{Zhang} , based largely on agricultural soil data, had the highest average AWC. A robust and independent test of PTF performance is critical to determining which of these PTFs is best suited for characterizing AWC given Swiss forest soil properties. The relationship between estimated AWC and the occurrence of extreme tree drought stress provides such a diagnostic.

4.2 Discoloration and AWC in the Swiss forest

4.2.1 Differences between PTFs

As expected, higher proportions of discoloration were generally observed at sites with lower AWC soils (Fig. 3). Several PTFs, including $AWC_{Wösten}$ and AWC_{Teepe} , strongly captured this signal in September 2018 (Fig. 4). Other PTFs like $AWC_{Puhlmann}$ and $AWC_{Wessolek}$ provided less clear relationships. These latter PTFs may be less suited to characterizing drought in Switzerland's European beech dominated forest soils, but there are no immediately clear methodological patterns which explain this relatively lower performance. The highest performing PTFs in our analysis (Table 2) including $AWC_{Szabó}$, $AWC_{Wösten}$, and AWC_{Teepe} all incorporate SOC and/or bulk density (Table 1) but other, lower performing (in the Swiss forest soil context), PTFs like $AWC_{Puhlmann}$ and AWC_{Saxton} also include these additional soil properties.

The generalizability of underlying PTF training data and its applicability to Swiss forest soils may go further in explaining PTF performance. For example, the lower performing PTFs of Zhang and Schaap (2017) and Saxton and Rawls (2006; Table 2) relied primarily on North American soil data for training. Weynants et al. (2009) based their training on an earlier, quite limited, dataset of Vereecken et al. (1989) which incorporated 33 Belgian agricultural soil profiles. The stronger performing PTF of Wösten et al. (1999) used (and established) the widely adopted HYPRES dataset which included 1777 agricultural soil profiles across western Europe (excluding Switzerland) and Tóth et al. (2015) and Szabó et al. (2021) used the extensive EU-HYDI dataset incorporating 6460 agricultural soil samples across Europe. The dataset used by Teepe et al. (2003) incorporated 1850 German forest soil profiles and these may generalize well to Swiss forest conditions.

The positive relationship between AWC_{Schoch} and discoloration proportion, where higher estimated AWC was associated with higher rates of discoloration in 2018, is somewhat surprising given that Schoch et al. (2025) specifically trained their PTF on Swiss forest soils. One likely contributing factor to this observation is the geographic distribution of their training data: most of the 1024 profiles used to train the PTF of Schoch et al. (2025) were concentrated on the Swiss plateau, the central plain between the Jura mountain range to the north and the Alps to the south (Fig. 1). The Swiss plateau is generally characterized by deep, and therefore naturally high AWC soils (Baltensweiler et al., 2021). A PTF calibrated predominantly on these conditions may extrapolate less reliably to the shallower or more skeleton-rich soils found elsewhere in the Swiss forest context, for example north of the Jura, where we observe substantial early leaf discoloration. If soils are assigned higher AWC than they hold, this could contribute to the positive relationship we observe between AWC and discoloration. A similar



335 consideration may apply to $AWC_{Puhlmann}$ (Table 2), whose training dataset of 1504 forest soil profiles, was drawn exclusively from the state of Baden-Württemberg in southern Germany. Both cases point to training-data representativeness, rather than PTF methodology, as a plausible driver of reduced transferability to the full range of Swiss forest conditions. $AWC_{Tóth}$, $AWC_{Szabó}$, AWC_{Teepe} and $AWC_{Wösten}$ provided the highest model performance and calibration in our single feature analysis at both 1 m and 2 m depths (Table S1 and Table 2).

340 **4.2.2 AWC at 1 m and 2 m depths**

Generally lower model performance at 2 m depth compared to 1 m depth across logistic regression models could arise from several factors. High discoloration rates in low-AWC soils are consistent with shallow or coarse soils, which hold less water. Elevated discoloration at some high-AWC sites, however, is less intuitive, and exposes a central question for interpreting AWC: under which soil conditions can roots actually access the water a profile is modelled to hold?

345 Modelled profile AWC may overstate the water available to trees, particularly at deeper depths. For example, the effective rooting depth at many plateau sites is likely shallower than a fixed 2 m aggregation depth. High-AWC plateau soils may also be subject to stagnic conditions, where waterlogging and anoxia restrict root penetration (Julich et al., 2021). These conditions could leave much of the modelled AWC below the depth roots can exploit. We did not attempt to test this hypothesis directly since rooting depth estimates themselves carry substantial uncertainty ($R^2 = 0.19$; Baltensweiler et al., 2021) and depend on

350 many factors beyond soil depth alone.

4.3 AWC as a piece of the drought stress susceptibility puzzle

AWC represents a potential, or the water a soil can theoretically hold. As such, water available in the soil for plants to use is not necessarily equivalent to AWC at any given time. The presence of water in the soil, which can be broken down into water filling prior to the summer season and water re-filling during the summer season, the pull of atmospheric demand during the summer, and the soil's ability to hold water (AWC) interact to form a site's inherent susceptibility to drought stress

355 (Meusburger et al., 2022). At the same time, vegetation structure and dynamics, for instance root depth, canopy cover, and water efficiency, compound with, and in some cases modulate, site conditions to determine an individual tree's disposition to drought stress (Klesse et al., 2022). As a sign of drought stress, early leaf discoloration is a product of these complex interactions.

360 Fully examining the drivers of early leaf discoloration and drought stress largely falls beyond the scope of this work but approximating some of the most impactful influences on site drought stress susceptibility allows us to more clearly examine the influence of different estimates of AWC. Winter and spring precipitation exceeded AWC across Switzerland in 2018 and most soil was at FC at the start of the summer season allowing us to hold this variable fixed. Atmospheric demand was roughly approximated based on maximum summer temperature and re-fill based on total summer precipitation. In combination with

365 these variables, $AWC_{Tóth}$, AWC_{Teepe} and $AWC_{Wösten}$ (Table 3) produced strong model calibration ($R^2 > 0.8$) and susceptible



site combinations with discoloration proportions of nearly 80% (Fig. 6). In many cases, AWC was the most important of the three variables.

Under exceptionally dry winter and spring conditions, summer precipitation is critical to limiting drought stress regardless of AWC (Fig. 7). However, even under fully filled start of summer conditions, like those of 2018, high atmospheric demand can quickly draw down available water (Fig. 7). In this case, AWC may play a larger role in determining which sites are susceptible to drought stress each year (Fig. 7). Sites with low AWC were associated with higher rates of early leaf discoloration in 2018, but extremely low AWC soils were also relatively uncommon (Figs. 5 and 6). Consequently, lower-probability discoloration on more common, moderately high-AWC, soils accumulated to a large absolute number of discolored pixels, limiting overall discriminatory performance (e.g., ROC-AUC < 0.7 and F1 score < 0.4; Table S2). In other words, the models reliably estimate the overall expected probability of discoloration but lack sufficient discriminatory power to individually separate discolored from non-discolored pixels. This likely comes down to factors like vegetation dynamics which govern an individual tree's drought susceptibility but are not captured within the simple model.

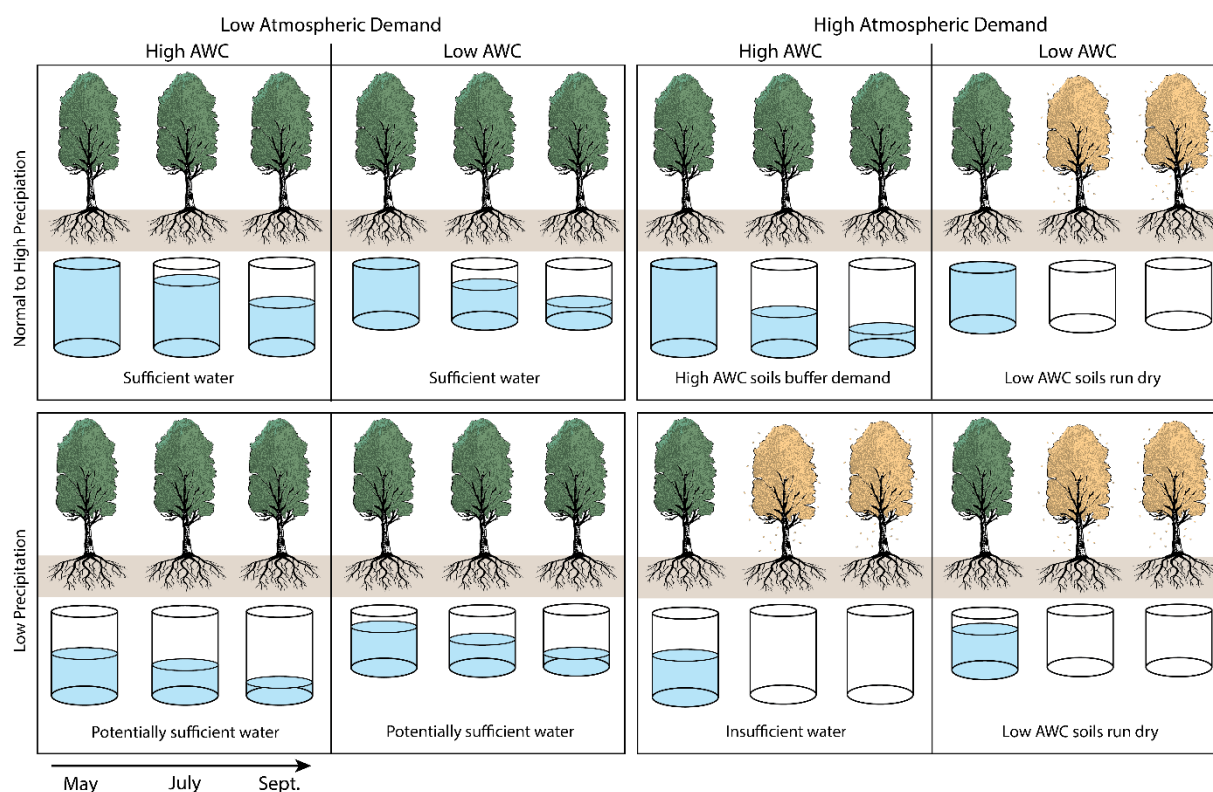


Fig. 7. Conceptual model of the relationship between AWC, precipitation, and high atmospheric demand.

The negative relationship we observe between discoloration and maximum temperature in our logistic regression models (Fig. 6) remains somewhat counterintuitive to a simple and idealized view of site drought susceptibility (Fig. 7). Summer temperatures in 2018 were generally high across all beech dominated sites, so a negative relationship could reflect a greater



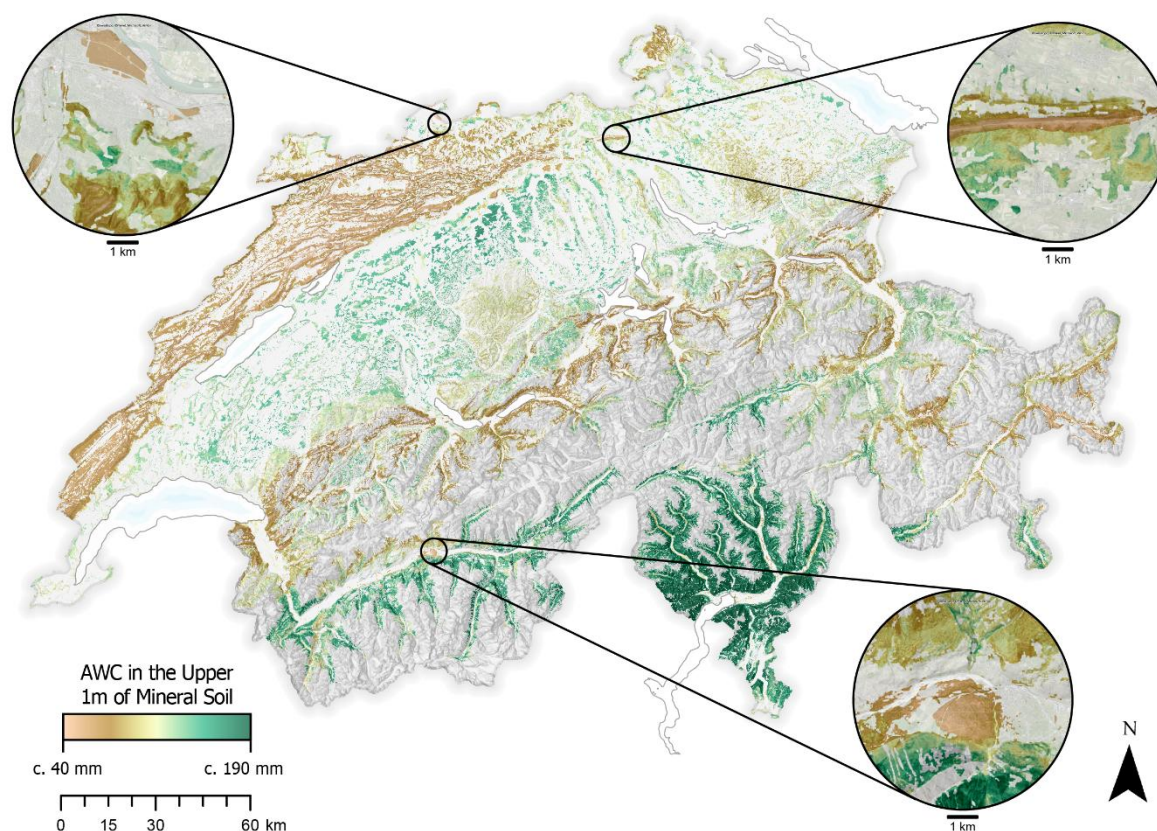
drought sensitivity in sites which normally experience cooler temperatures, leaving them less well adapted to hot and dry conditions. Alternatively, maximum summer temperature in 2018 may simply correlate with other important variables which are not included in our models. Limitations in the underlying discoloration, soil and meteorological datasets used to model discoloration (described in greater detail in Sect. 4.5) could also contribute to counterintuitive model coefficients and lower overall model performance. Additional investigations of early leaf discoloration drivers are warranted and may add to our understanding of the role of AWC in drought stress susceptibility.

4.4 High resolution AWC maps for the Swiss forest and additional applications

AWC_{Wösten} and AWC_{Teepe} delivered consistently strong performance both individually and in combination with meteorological conditions in 2018 (Tables 2 and 3). We feel confident that either of these PTFs could provide sufficient fidelity for high resolution AWC maps of the Swiss forest on their own. That said, settling on a single PTF across the Swiss forest is largely unnecessary, when several offer complementary separability of drought stress conditions.

For our final 1 m and 2 m AWC maps (Fig. 8), we chose the mean of four PTFs: AWC_{Szabó}, AWC_{Tóth}, AWC_{Teepe}, and AWC_{Wösten}. These PTFs tend towards the center of the value range of PTFs that we examined (Fig. 2) and offer relatively high performance in separating drought stress in European beech (Tables 2 and 3, Figs. A1 to A3). These PTFs were trained using a broad range of underlying European forest soil conditions and offer methodological diversity (Table 1). Incorporating multiple PTFs into our estimates of AWC for the Swiss forest also allows us to provide uncertainty estimates (e.g., $\pm 1\sigma$ across PTFs) which enhance the usability of the dataset.

Beyond their role in drought susceptibility assessment and as inputs into SVAT models (both previously discussed), 25 m AWC maps for the Swiss forest have broad potential application across forest management and forest ecology. For instance, AWC modulates when thermal and hydraulic tolerance thresholds may be crossed, altering a species' site-suitability. Incorporating the fine spatial scales of these updated AWC layers into species distribution models could, therefore, improve projections of range shifts for temperate forest species under future climate scenarios. At the stand level, silvicultural planning also increasingly requires spatially explicit soil water information. The AWC layers produced here could directly inform decisions about stand suitability for intervention and species composition conversion. Finally, forest carbon models remain sensitive to drought-induced growth reductions and mortality, and the spatial products provided here could help constrain uncertainty in national and regional carbon inventories.



410 **Fig. 8.** Mean 25 m AWC in the upper 1 m of Swiss forest soils derived from four PTFs (Szabó et al., 2021; Tóth et al., 2015; Teepe
 et al., 2003; and Wösten et al., 1999). The national basemap is represented by a hill shade derived from swissALTI3D (swisstopo,
 2024a) and the inset basemaps are extracts from SWISSIMAGE (swisstopo, 2024b).

4.5 Limitations and additional areas for ongoing investigation

Most PTF evaluations rely on laboratory measurements at point locations. We were able to leverage the extreme drought year
 415 2018 as a natural experiment to examine PTF performance across hundreds of thousands of sites. Naturally, this limits our
 evaluation to gridded soil datasets with their own uncertainties and limitations. The digital soil maps of Baltensweiler et al.
 (2021) which we apply in this analysis were trained on a limited number of soil profiles across Switzerland, many of which
 were located on the relatively high AWC soils of the Swiss Plateau. Uncertainties in the applied soil maps inherently propagate
 into the AWC maps presented herein representing the single largest limitation in our analysis. Soil map uncertainty may help
 420 to explain the low deterministic power of our models and could have an influence on the representativeness of AWC from
 some of the applied PTFs. Quantifying uncertainty propagation in this context, however, is extremely challenging. Future
 efforts to develop larger, more spatially balanced soil databases, alongside more complex modelling approaches, could help
 reduce uncertainties in high resolution digital soil maps and, ultimately, in AWC estimates.



Soil properties that we have not explicitly accounted for, namely rock fragment porosity and forest floor organic layers, may also represent potentially meaningful sources of unmodelled AWC in the Swiss forest. Rock fragment porosity is likely geologically variable across Switzerland's diverse lithologies, and while Tetegan et al. (2011) demonstrated that it can exert a strong influence on total AWC, no comprehensive characterization exists in the Swiss soil context. Forest floor organic horizons may similarly contribute to plant-available water storage, though depending on the site, they may be prone to rapid desiccation or be missing at many lower-elevation beech sites. The importance of forest floor organic layers is likely greater for assessments of coniferous species at higher elevations where slower decomposition rates produce thicker accumulations of organic material. Modelling the depth of these organic layers directly from profile level observations is the focus of our ongoing work.

While the discoloration-AWC relationship presented herein offers a unique opportunity to examine PTF performance, the results are implicitly optimized for the digital soil maps of Baltensweiler et al. (2021), the year 2018, and drought affected trees in Switzerland's European beech dominated forests, which are challenging to constrain themselves (Bloom et al., 2026). The results may not transfer directly to conifers or to other broadleaved species with different drought response mechanisms. More severe future droughts, combined with active forest monitoring systems, will offer further opportunities to test and refine these relationships across a broader range of species and stress conditions.

As a critical final note, Swiss forest soils, characterized by high organic matter content, steep terrain, and shallow rocky profiles, may fall outside the calibration domain of several of the PTFs which we examined, for instance the agricultural lowland soils used by Wessolek et al. (2009). As such, the results here do not invalidate any of the PTFs that we examined.

5 Conclusions

Using the extreme drought year 2018 as a natural experiment, we benchmarked ten pedotransfer functions applied to a common set of high-resolution digital soil maps against satellite-derived early leaf discoloration observations across hundreds of thousands of forest sites in Switzerland, identifying the PTFs of Teepe et al. (2003) and Wösten et al. (1999) as the most robust estimators of AWC under Swiss forest conditions. Combining AWC with total summer precipitation and maximum summer temperature only modestly improved model discrimination but helped identify site combinations with particularly high discoloration risk. Discoloration proportions reached nearly 80% in the most susceptible site combinations. The resulting 25 m AWC maps represent the highest resolution validated soil water products available for Swiss forests to date and provide spatially explicit uncertainty estimates through a multi-PTF ensemble approach. Critically, the mapped values and the relative performance of individual PTFs remain dependent on the underlying digital soil maps. Transfer to other regions, forest types, or soil datasets will require independent evaluation rather than direct adoption of the selected PTF ensemble. Nonetheless, the benchmarking method itself is directly transferable to other broadleaf-dominated forests where satellite-derived stress indicators and digital soil maps are available. As summer droughts in Central Europe become more frequent and severe, the



455 products and methods developed here provide an immediately applicable foundation for adaptive forest management, early warning systems, and national carbon accounting.

Appendix A

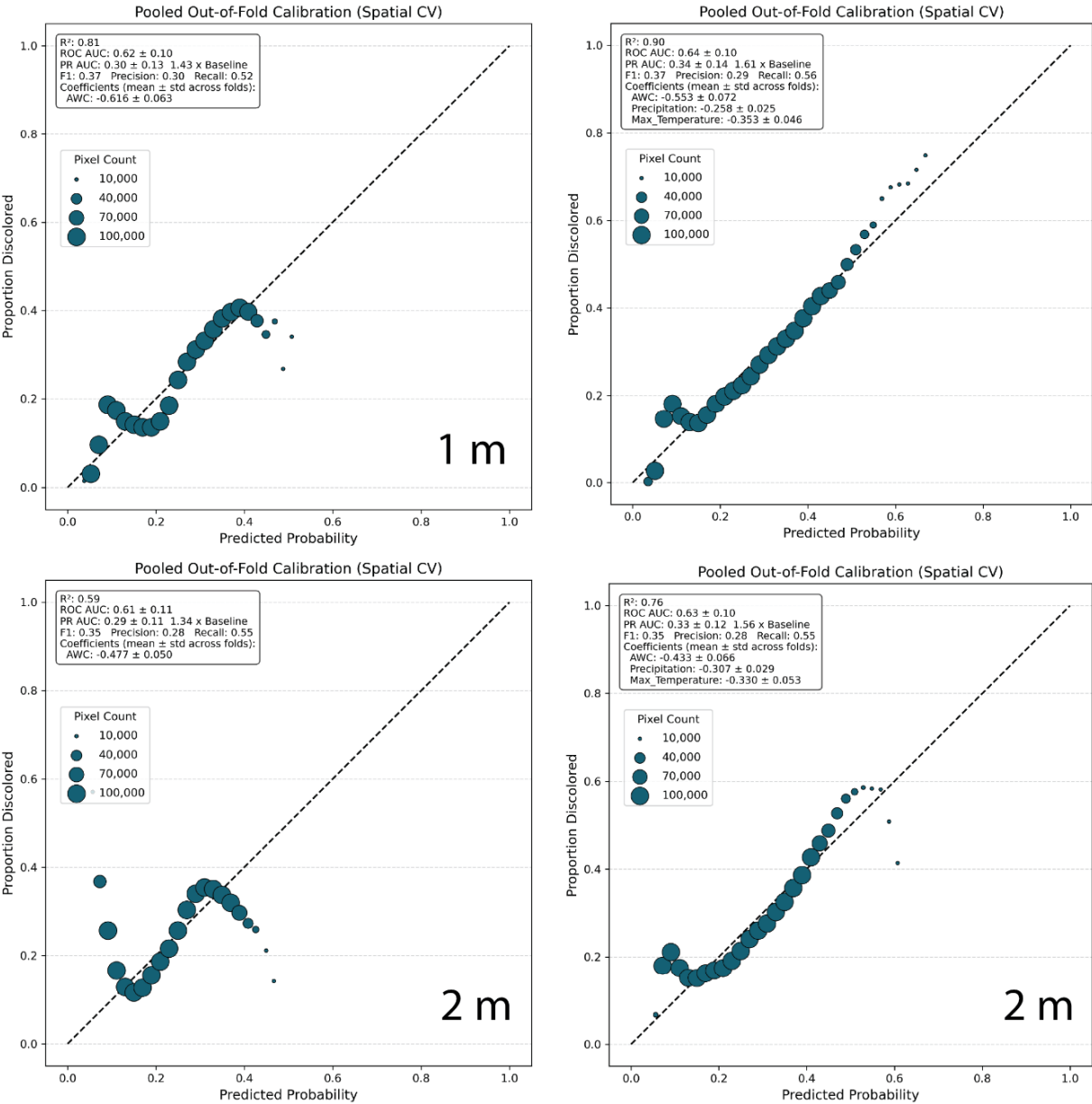


Fig. A1. Logistic regression model fits using optimized mean AWC from 4 PTFs (Wösten, Teepe, Tóth, and Szabó)



460 We applied the models trained on the optimized mean AWC dataset (Fig., A1) to the years 2017 to 2022 using data on early
 leaf discoloration from Bloom et al. (2026) and the derived meteorological datasets described in Sect. 2.2.3. Applied to less
 extreme drought years in Switzerland (e.g., 2017, 2020, and 2022), the models showed modest discoloration separability (Figs.
 A2 and A3). Applied to non-drought years (2019 and 2021), the models performed worse than random (ROC-AUC < 0.5;
 Figs. A2 and A3); however, this likely reflects noise from a very small number of discolored pixels classified in these non-
 465 drought years rather than a genuine failure to detect discoloration.

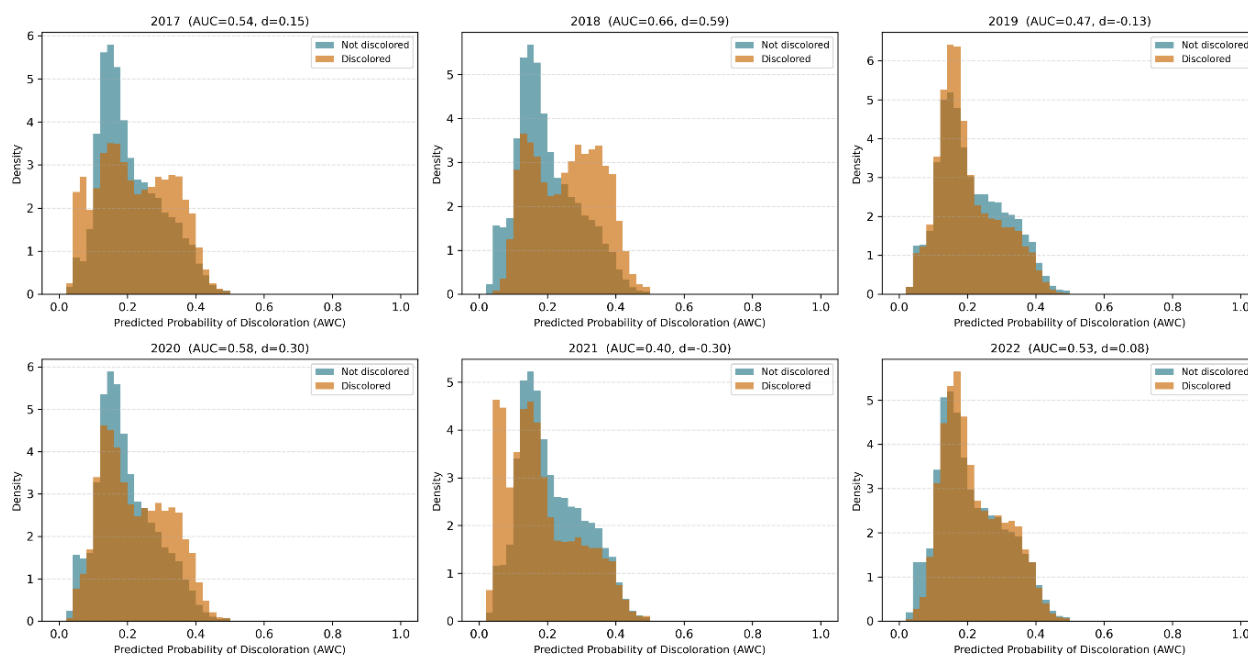


Fig. A2. Multiannual application of logistic regression models of early leaf discoloration trained using AWC_{wuesten}.

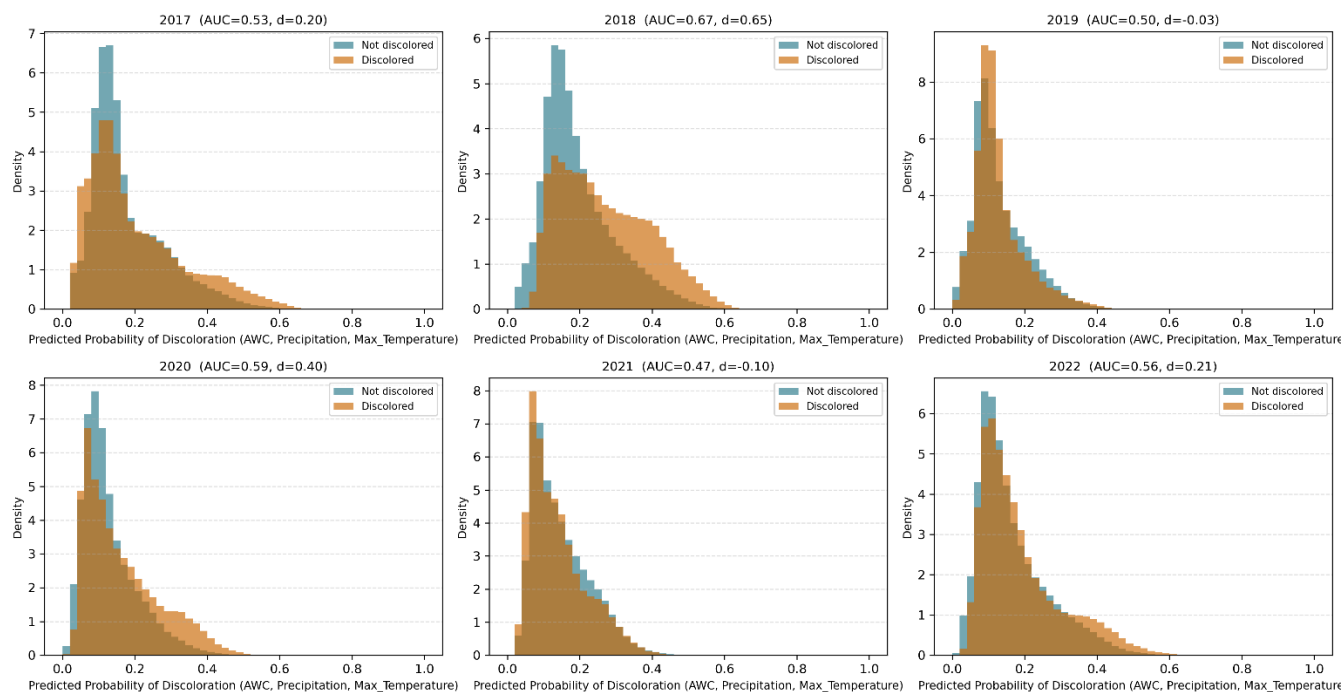


Fig. A3. Multiannual application of logistic regression models of early leaf discoloration trained using $AWC_{W\ddot{o}sten}$, summer total precipitation, and maximum summer temperature.

Code and data availability

The digital soil maps used in this study (Baltensweiler et al., 2021) are publicly available via EnviDat at <https://www.doi.org/10.16904/envidat.484>. The early leaf discoloration data (Bloom et al., 2026) are described by a metadata record on EnviDat at <https://www.doi.org/10.16904/envidat.786>; the full discoloration dataset can be obtained on request from the corresponding author. Daily meteorological data (precipitation, temperature, and dewpoint temperature) were obtained from Meteotest and are not publicly available; readers seeking access to the underlying daily data should contact Meteotest directly. Reviewers requiring access to the daily meteorological data to reproduce the full analysis during the review process can obtain the daily meteorological data on request from the corresponding author. Seasonal meteorological derivatives can be obtained on request from the corresponding author. The code used to perform the analyses in this study is available on GitHub at <https://github.com/ckbloom/bloom-et-al-2026-AWC>. The optimized AWC maps and uncertainty estimates generated in this analysis are available via EnviDat at <https://www.doi.org/10.16904/envidat.808>.



Author contributions

485 CB and KM conceptualized the analysis. CB carried out the formal analysis and prepared the original draft. KM, LW, and AB reviewed and edited the manuscript. AB acquired funding for the study.

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