Cross-comparison of national drought monitoring products in Central Europe using a new drought impact database

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S1 Impact data count

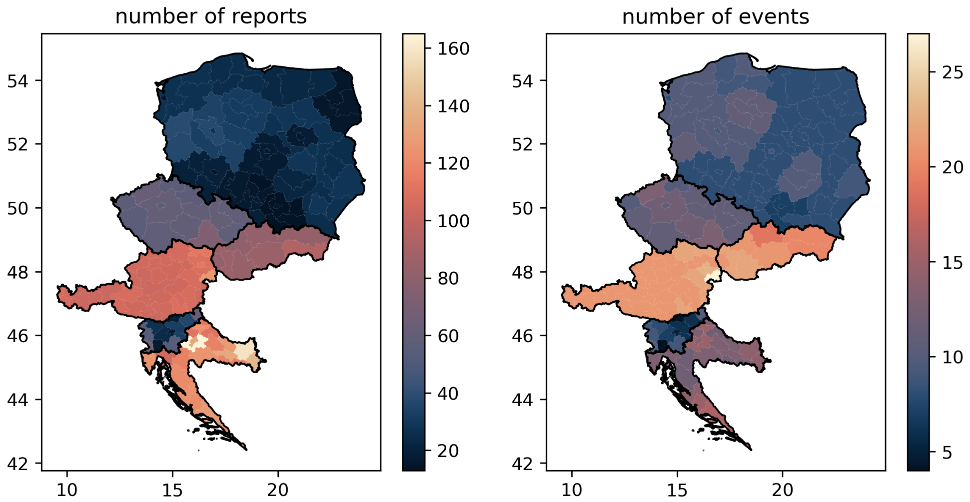

Fig. S1 Number of drought impact entries and number of drought impact events (ID) per NUTS3 region in Central Europe

S2 National drought monitoring products

Austria: Geosphere Austria disseminates drought related information via its data hub (https://data.hub.geosphere.at/dataset/winfore-v2-1d-1km). The main drought monitoring product of Geosphere Austria is standardized precipitation evapotranspiration index (SPEI), which measures the balance between precipitation and potential evapo-transpiration (PET) over time. It is based on daily temperature and precipitation data from Spatiotemporal Reanalysis Dataset for Climate in Austria (SPARTACUS), which is developed by interpolating in-situ observations in Austria onto a regular grid (Hiebl and Frei 2016, 2018). The PET for SPEI is calculated using the optimized Hargreaves method (Hargreaves and Samani 1985). The SPEI data at 1, 3, and 12 month aggregation periods are available from 1961 to the present at a daily time step. For our study, we downloaded the SPEI data from the data hub for the period 2000-2023.

Croatia: The Croatian Meteorological and Hydrological Service (DHMZ) provides standardized precipitation index (SPI) and SPEI at 1, 2, 3, 6, 9, 12, 18, and 24-month aggregation periods, updated monthly on its online platform (https://meteo.hr/klima_e.php?section=klima_pracenje). The drought data are computed from in-situ time series of daily precipitation and temperature data measured at the meteorological stations managed by DHMZ. The PET for SPEI is calculated using the modified Hargreaves-Samani formula (Droogers and Allen 2002; Hargreaves and Samani 1985). The calibration period for the both indices is 1981-2020. Before implementing the SPEI in operational monitoring system, a detailed analysis for its suitability was performed (Lončar-Petrinjak et al. 2024). The data are publicly available for the 10 most recent years. The SPI and SPEI were provided by DHMZ up on request.

Czechia: In Czechia, Global Change Research Institute of the Czech Academy of Sciences (CzechGlobe) employs relative soil moisture (AWR), derived from the SoilClim model (Hlavinka et al. 2011; Trnka et al. 2020) as a basis for its drought monitoring product. AWR represents the soil saturation level between wilting point and field capacity. SoilClim, a semi-empirical water balance model, simulates daily AWR at various soil depth intervals (0-10 cm, 0-40 cm, 0-100 cm, and 0-200 cm) using several meteorological inputs. AWR values are categorized to represent different levels of drought intensity based on climatology. CzechGlobe produces AWR and categorized drought levels derived from AWR data at 500 m (Trnka et al. 2020) and 0.1 degree (Řehoř et al. 2021) resolutions. This study utilises the 0.1 degree product generated with ERA5-Land data as forcing. The product is available not only for Czechia but also for all other countries considered for this study (https://www.windy.com). AWR values, instead of categorized drought levels, were used for comparison due to their temporal and spatial aggregation potential. Data from 1981-2023 for 0-40 cm and 0-100 cm depths, were acquired from the CzechGlobe up on request, and aggregated for different periods, and then standardized using the method described in Section "Data harmonization" in the main text.

Poland: The national drought monitoring product of Poland is focused on agricultural drought impacts on specific crop types and archived data are only available at seasonal scale, which is not suitable for the assessment framework of this study. For this reason, for our assessment in Poland we use AWR data from CzechGlobe instead of the official national drought monitoring product.

Slovakia: In Slovakia, Slovak Hydrometeorological Institute (SHMI) produces SPEI and SPI data for drought monitoring. The SPI and SPEI are calculated at a daily time step with a 1-month aggregation period. They are based on the daily precipitation and temperature data from their meteorological stations, where PET for SPEI is calculated using the Penman-Monteith method (Penman 1948; Monteith 1965). The drought information based on these products is publicly accessible through their website (https://www.shmu.sk/en/?page=2161).

Slovenia: The Slovenian Environmental Agency (ARSO) operates the drought monitoring system in Slovenia, which is based on a (surface) water balance data. The surface balance is computed as the difference between precipitation and reference evapotranspiration, where the latter is computed using the Penman-Monteith method (Penman 1948; Monteith 1965). The data are available as 1-month floating averages at 10-day time steps. The percentile values of the surface balance at each in-situ observation station are used to generate drought products, which are made available through Susometer (https://meteo.arso.gov.si/uploads/probase/www/agromet/bulletin/drought/sl/). Surface balance data from 1981-2023 were requested from ARSO and then standardized following the method described in Section ”Data harmonization” in the main text.

S3 Spatial distribution of validation metrics for AWR-based indices

S3.1 Drought detectability analysis

Fig. S2 shows the spatial distribution of AUC values for AWR-based indices, with different aggregation periods, which are the only ones available for all the countries. Shorter aggregation windows generally yield better performance, with many NUTS2 regions achieving AUC values above 0.7. The performance declines with longer aggregation periods, except for northern Poland. The spatial distribution of the AUC values shows a large impact of the country on the performance, i.e., Austria shows a low performance for all NUTS2 regions, all other countries, except for Poland, show consistently high AUC values. Only in Poland, we can see a large range of AUC values for an aggregation time of 12 months.

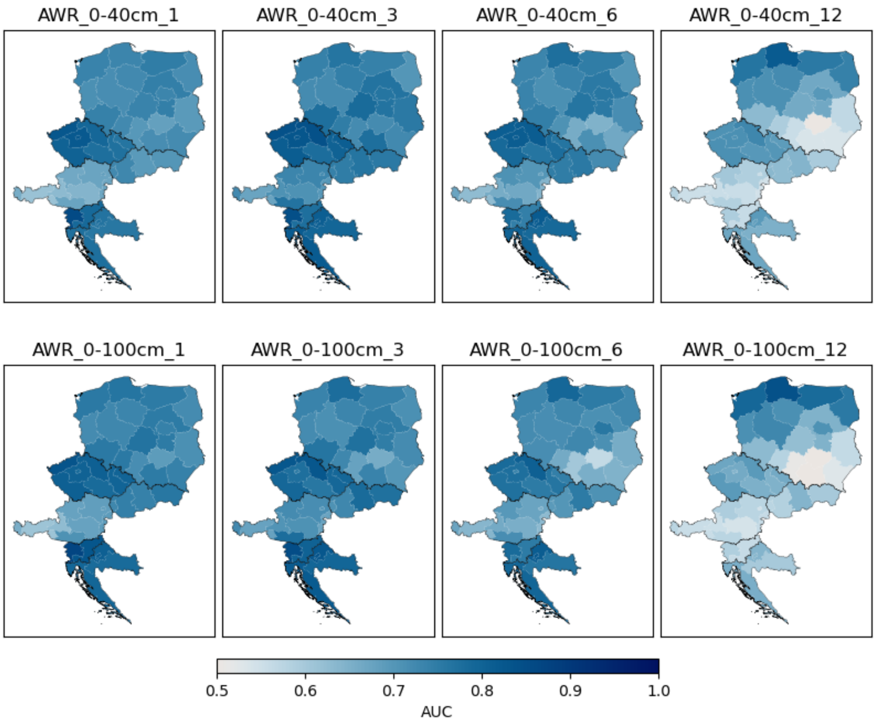

Fig. S2 Spatial distribution of AUC values for AWR-based indices for different aggregation periods (1 3, 6, 12 months), which are the only ones available in every country. The last part of the index name shows the aggregation time of the index.

S3.2 Severity analysis

The spatial distribution map (Fig. S3) of the correlation values for the AWR-based indices shows regional differences in the change in correlations with aggregation periods, as observed in the boxplots (Fig. 7 in main article). The different relationship correlations have with aggregation period in different countries leads to an interesting north-south gradient. For shorter aggregation periods of 1, 3 and 6 months, correlations generally decrease from north to south. However, increasing the aggregation period from 6-months to 12-months, correlations in the north fall sharply, while in the south they remain more stable or even increase. This leads to reversed north-south gradient for 12-months aggregation period. However, the correlations at 12-month aggregation period in most of the NUTS2 regions are not statistically significant (larger p-values).

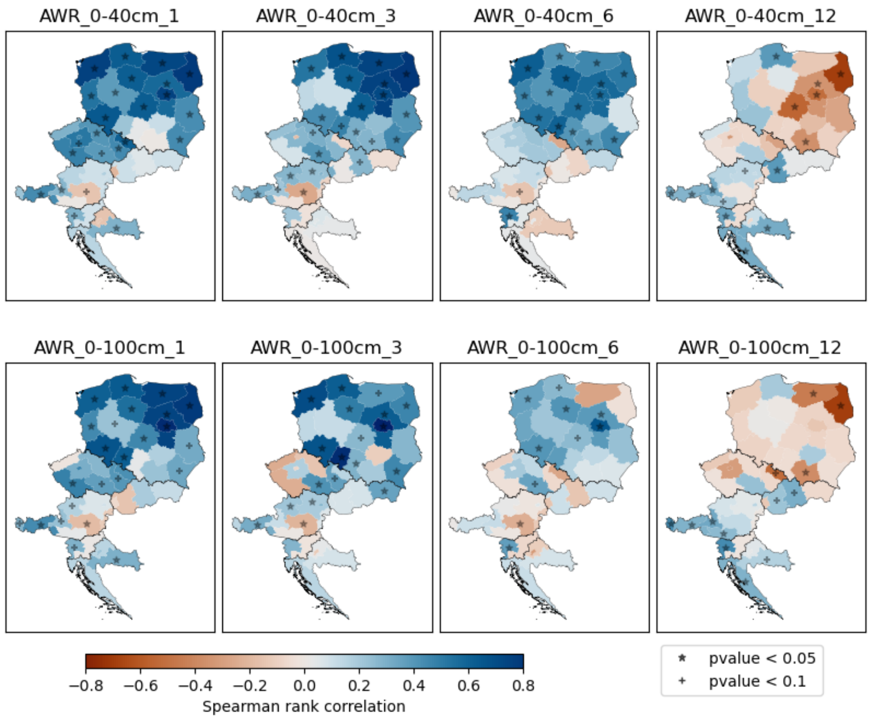

Fig. S3 Spatial distribution of correlation coefficient between drought severity and number of reported impact at the NUTS2 regions for AWR-based indices, which are the only ones available in all the countries. The star and plus symbols show that the correlation values are statistically significant at 5% and 10% significance level, respectively. The last part of drought index indicate the aggregation time

S4 Impact on agriculture

In case of agriculture-related impacts, the performance of drought indices in capturing the occurrences and, to some extent, the severity of the impacts, follows a similar pattern as those observed for all types of impacts lumped together. This is likely due to the fact that the agriculture-related impact type is the most numerous one in the impact database, and hence dominates the results for overall impacts. Additional data from other impact categories need to be collected to analyse in more detail the impact of skewed data on the results.

Furthermore, drought indices based on soil moisture at deeper layers capture the drought impacts on agriculture more effectively. This aligns with the assumption that crops are primarily affected by the dryness in root zone, from where the plants extract water, and which generally covers the depth interval 0-100 cm. Further, drought indices with a longer aggregation period better capture the impact severity. This signals that the long-term changes in moisture availability has stronger influence on crop conditions.

S4.1 Detectability of impact occurrence on agriculture

The spatial pattern of best performing drought indices for drought occurrence detection for only the agricultural sector (Fig. S4) is similar to that for all sectors lumped together, with slight differences in Poland, Czechia, Slovakia and Austria. In a few regions in Poland, Czechia, and Slovakia, AWR at 0-100 cm becomes more relevant for agricultural drought impact, while in Austria AWR at 0-40 cm becomes more relevant. Further, the best performing indices shift towards the shorter aggregation period in these regions. In addition, the highest AUC values also increase slightly, particularly in Poland, Czechia, and Croatia. The relationship between AUC values and aggregation period for agricultural drought impacts is similar to that of impacts across all sectors (Supplementary Fig. S4)

S4.2 Detectability of impact severity on agriculture

The spatial distribution of the best correlation values and corresponding drought indices when considering only the agriculture-related impacts S5 shows a slight deviation from that observed when considering all the impact sectors (Fig. 8 in main

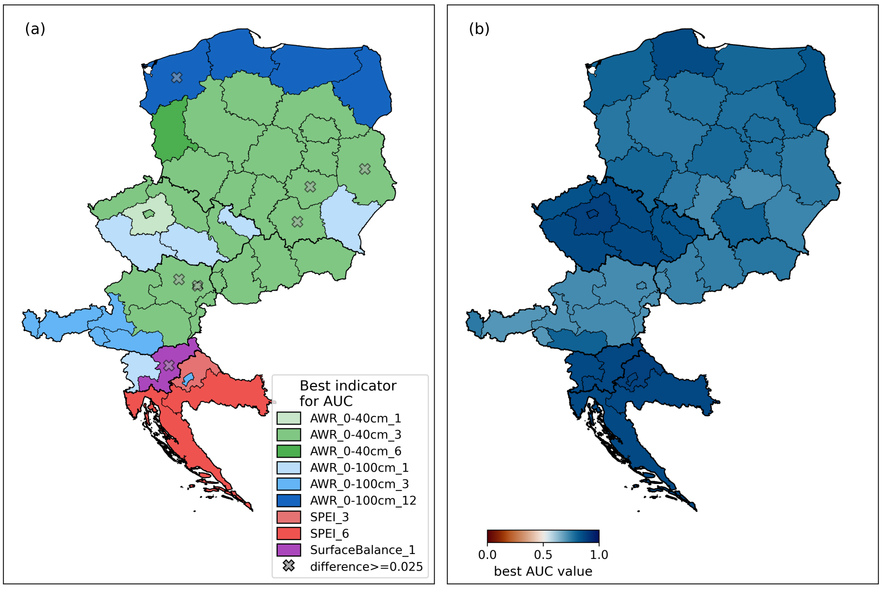

Fig. S4 The drought indices with (a) the highest AUC values at each NUTS2 region and (b) corresponding AUC values for drought impact on agriculture. The cross symbol marks NUTS2 regions where the difference in AUC values between the best and the second best indices is more than 0.025. The last suffix of the index name shows the aggregation time of the index in months. AWR-based indices are available for all the countries, SPI-based indices are available for Slovakia and Croatia, SPEI-based are available for Austria, Slovakia, and Croatia, SurfaceBalance is available only for Slovenia.

article). The soil moisture based drought indices, particularly in the column of 0-100 cm, and drought indices with longer aggregation periods, become more relevant for agricultural impact detection, compared to overall impacts. In western Austria and southern Croatia, the AWR-based indices emerge as best performing index, replacing the precipitation-based indices (i.e., SPI, SPEI). In some regions in Poland, western Slovakia, and western Slovenia, AWR 0-100cm-based indices outperform AWR 0-40cm-based indices when considering only agricultural impacts. Even when the drought index family remains the same, the index with a longer aggregation period tends to better capture the agricultural impacts. Furthermore, a large part in Czechia is masked out due to insufficient data for agricultural impacts.

Fig. S6 shows that the drought indices capture the impact occurrence on agriculture sector quite similarly to that of overall impacts on all sectors (Figure 5). The AUC

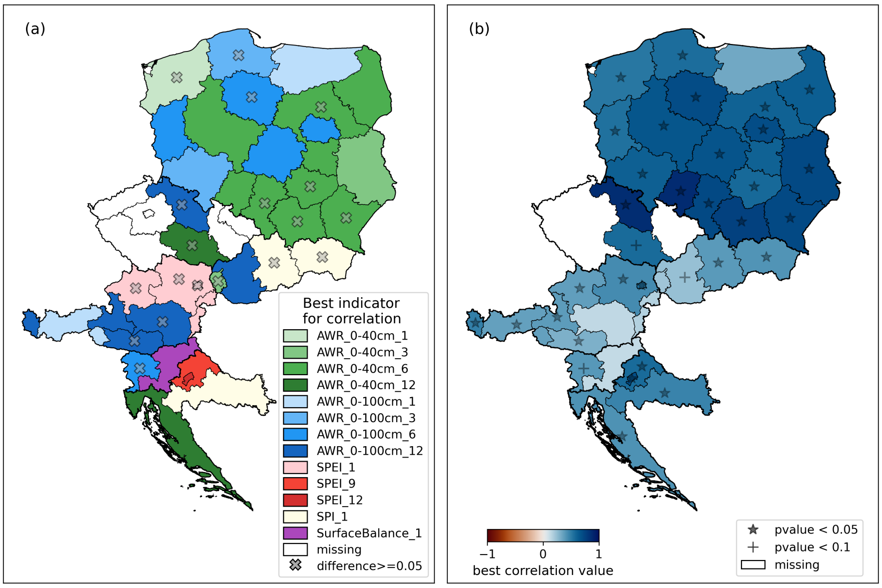

Fig. S5 (a) The drought index for each NUTS2 region with the highest Spearman correlation values against agriculture impacts, and (b) the corresponding correlation values. The cross symbol marks NUTS2 regions where the difference in correlations between the best and the second best index is more than 0.05. The star and plus symbols show the NUTS2 regions where the correlation values are statistically significant at 5% and 10% significance level, respectively. The last suffix of index name shows the aggregation time of the index in months. AWR-based indices are available for all the countries, SPI-based indices are available for Slovakia and Croatia, SPEI-based are available for Austria, Slovakia, and Croatia, SurfaceBalance is available only for Slovenia.

values peak at higher values in Czechia and Croatia for agriculture related impacts than the overall impacts, that is, drought indices capture the agriculture impacts better than the overall impacts in these countries. Elsewhere, while the distribution of AUC values changes, the differences in overall performance are small.

With regard to the relationship of correlation values and aggregation period between the overall impacts and agricultural impacts, there are notable differences in Czechia, Slovenia and Croatia. In Czechia, the correlation values increase with aggregation period for agricultural impacts, on contrary to the pattern observed for overall impacts, although the data availability decreases while considering only agricultural impacts. In Slovenia, higher fluctuation in correlation values are observed for agriculture impact type compared to overall impacts. In Croatia, the correlation values for

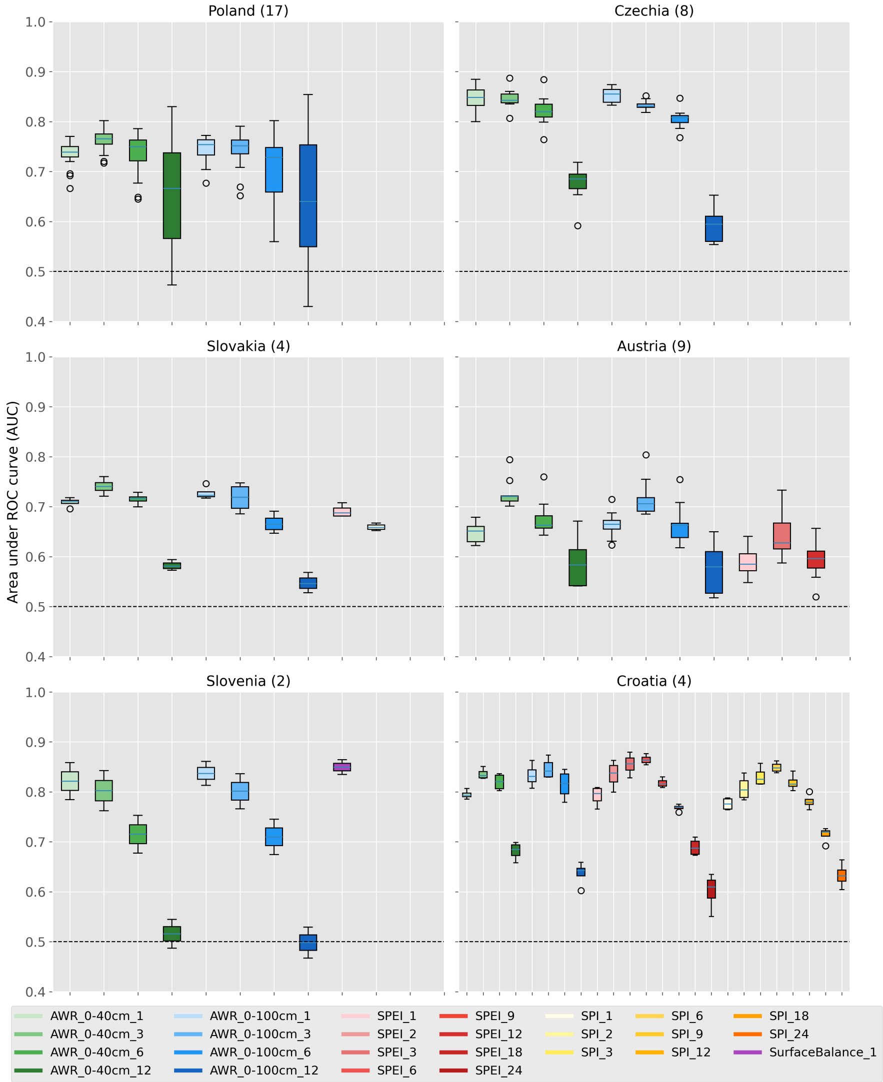

Fig. S6 AUC values with agriculture impact category for drought indices across different aggregation periods available in each country using distinct colors at the NUTS2 level (the number of NUTS2 regions per country is indicated in parentheses). The last part of the index name shows the aggregation period of the index.

SPI follow a similar pattern to that of AUC values for agriculture impact, which is not the case with overall impacts.

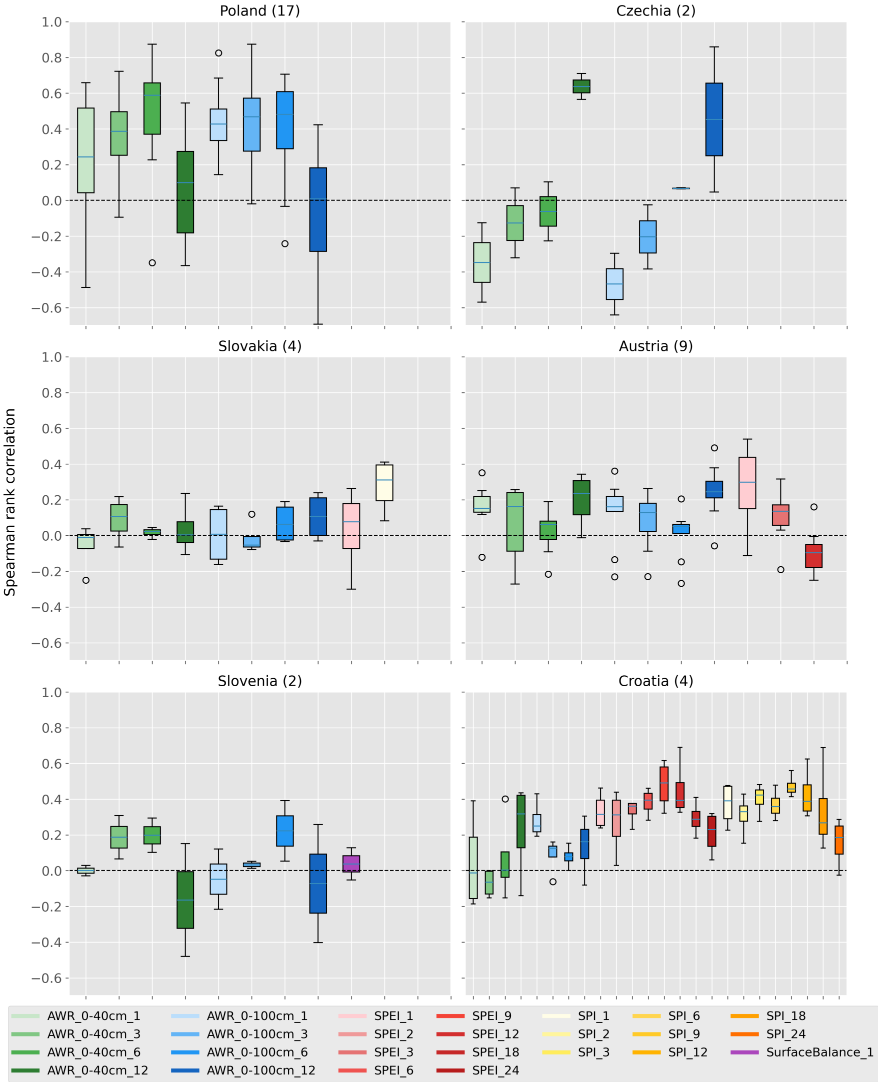

Fig. S7 Correlation between drought severity calculated from drought index and the number of impacts on agriculture sector reported in the impact database for drought indices across different aggregation periods available in each country using distinct colors at the NUTS2 level (the number of NUTS2 regions per country is indicated in parentheses). The last part of drought index indicate the aggregation time.

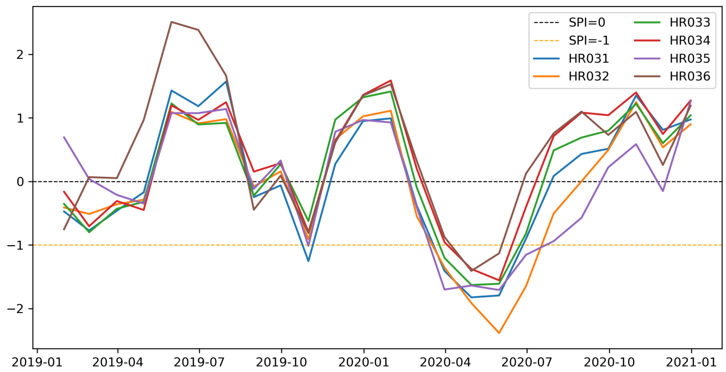

Fig. S8 SPI-3 timeseries of NUTS3 regions in Adriatic part of Croatia showing that the drought index fell below -1.

S5 Example of impact reports missing out on short scale drought

Fig. S8 shows that the SPI-3 values for all the NUTS3 regions in Adriatic part of Croatia fell below -1 for the month of April and May. The SPI-3 for each of the NUTS3 regions in this part of Croatia dropped below -1 for two months in April and May, but then quickly returned to normal with the rainfall in late June and July . This sharp decrease in drought index was not reported in the newspaper articles that year. So, there was no drought impact reported in the region in our impact database. The reason for no reported impact could be either the drought lasted quite short and did not affect the crops planted during that time or public was prepared to adjust to the short-term drought. This shows that the impact database does not capture all the drought episodes occurring at small scale.

S6 Example of delayed reporting of drought impact

Drought impacts are not necessarily visible or reported at the same time when the drought is developing or at its peak. Drought indices usually capture the developing drought conditions earlier, which is important for drought monitoring. Ideally, we want to know when to expect drought impacts, i.e., the time elapsed after a certain drought index value drops below -1. However, due to the diversity in impact types and because no two drought events evolve in the same way, such a generalization is not feasible. The impacts are typically observed later, as the drought matures. For instance, crop yield losses are usually reported after the harvest, because only then the impacts can be quantified. However, the drought caused its damage (much) earlier in the season. This causes delay in reporting of drought impact. These kind of delays in impact reports were found in the impact database. For example, there was a strong drought in spring of 2020 in a region in Lower Austria, but the crop yield losses were reported only after harvest in the autumn of that year, after the drought episode ended in the summer (Fig. S9).

Fig. S9 shows an example of delayed of reporting of impact of drought on agriculture. In 2018, drought developed during the spring and continued through the summer in AT123 NUTS3 region in Lower Austria. This drought adversely affected plant health during the growing stages and hence caused crop yield losses. However, the yield loss was reported only when the farmers harvested the crop in late summer or early autumn. The drought episode delineation detects the drought in spring and corresponds to the reported impacts.

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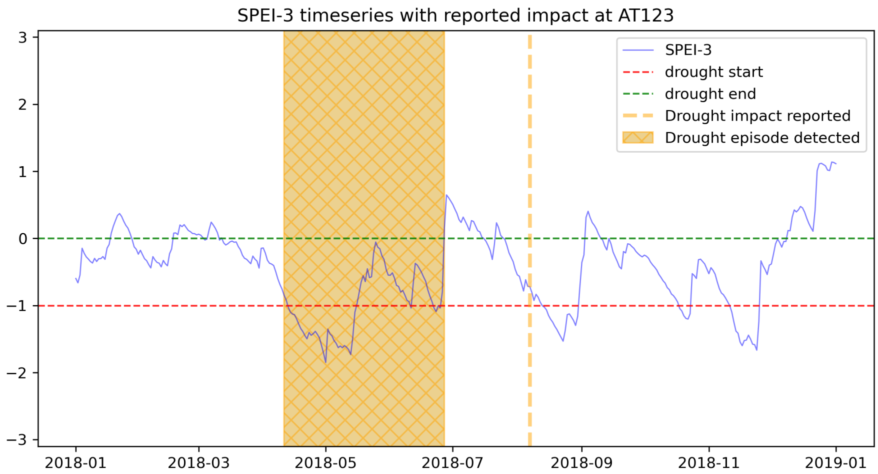

Fig. S9 SPEI-3 timeseries of a NUTS3 region in Lower Austria showing delayed reporting of drought impact.

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