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Discussions

1 **The impact of drought on the productivity of two rainfed crops in Spain**
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7

8 **Abstract**

9 Drought events are of great importance in most Mediterranean climate regions because of the diverse and costly impacts they
10 have in various economic sectors and on the environment. The effects of this natural hazard on rainfed crops are particularly
11 evident. In this study the impacts of drought on two representative rainfed crops in Spain (wheat and barley) were assessed.
12 As the agriculture sector is vulnerable to climate, it is especially important to identify the most appropriate tools for monitoring
13 the impact of the weather on crops, and particularly the impact of drought. Drought indices are the most effective tool for that
14 purpose. Various drought indices have been used to assess the influence of drought on crop yields in Spain, including the
15 standardized precipitation and evapotranspiration index (SPEI), the standardized precipitation index (SPI), the Palmer drought
16 indices (PDSI, Z-Index, PHDI, PMDI), and the standardized Palmer drought index (SPDI). Two sets of crop yield data at
17 different spatial scales and temporal periods were used in the analysis. The results showed that drought indices calculated at
18 different time scales (SPI, SPEI) most closely correlated with crop yield. The results also suggested that different patterns of
19 yield response to drought occurred depending on the region, period of the year, and the drought time scale. The differing
20 responses across the country were related to season and the magnitude of various climate variables.
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22 **Key words:** crop yields, drought, Spain, standardized precipitation index, standardized precipitation evapotranspiration index,
23 standardized Palmer drought severity index
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1. **Introduction**

The Mediterranean region is one of the major areas in Europe likely to be subject to the potential impacts of climate change. Many semiarid regions of southwestern Europe are expected to undergo a critical decline in water availability as a consequence of reduced precipitation and an increase in interannual and intra-annual rainfall variability (IPCC, 2014, EEA, 2017). It is also expected that future changes in the precipitation regime, along with a rise in temperature, will inevitably bring more extreme and severe weather events (Giorgi and Lionello, 2008; Webber et al., 2018; Wigley, 2009) that will impact ecosystems and economic sectors (Asseng et al., 2014; Tack et al., 2015). It has been suggested that precipitation and temperature changes in the western Mediterranean region will lead to more severe and longer drought events in coming decades (Alcamo et al., 2007; Dai, 2011; Forzieri et al., 2016; Giorgi and Lionello, 2008; Spinoni et al., 2018; Vicente-Serrano et al., 2014). This is significant because agriculture plays a key role in food supply; in 2017 it accounted for 2.59% of GDP in Spain, 1.92% in Italy, and 3.53% in Greece (World Bank, 2017).

The agriculture sector is highly vulnerable to drought, as it depends directly on water availability (Hanjra and Qureshi, 2010; Meng et al., 2016; Tsakiris and Tigkas, 2007). Although each crop differs in its resilience to water stress (Liu et al., 2016; Lobell et al., 2011), droughts can cause crop failure if the weather conditions are adverse during the most sensitive stage of crop growth (Lobell and Field, 2007). The adverse impacts of drought have been highlighted in recent severe events, including in 2003 when the agricultural and forestry losses from drought in France, Italy, Germany, Spain, Portugal, and Austria were approximately 13 billion Euros (Fink et al., 2004; García-Herrera et al., 2010). The most recent drought, which mostly affected north–central Europe, caused European farmers to claim agricultural aid because of the low production that resulted (European Commission, 2018).

For these reasons the vulnerability of agricultural production to extreme events, and the quantification of drought impacts on crop yields, have become a focus of interest. In recent years diverse studies in the Mediterranean region have assessed these issues from multiple perspectives. For example, Capa-Morocho et al., (2016) investigated the link between seasonal climate forecasts and crop models in Spain, Loukas and Vasiliades, (2004) used a probabilistic approach to evaluate the spatio-temporal characteristics of drought in an agricultural plain region in Greece, and Moore and Lobell, (2014) estimated the impacts of climate projections on various crop types across Europe.

Droughts are difficult to measure and quantify (Vicente-Serrano et al., 2016), and consequently a wide range of drought indices has been developed to provide tools for quantifying the effects of drought across different sectors (Zargar et al., 2011). In this respect, drought indices are the most widely used method for monitoring drought impacts on agriculture; examples of their use available in the scientific literature include in Europe (Hernandez-Barrera et al., 2016; Potopová et al., 2016a; Sepulcre-Canto et al., 2012; Vergni and Todisco, 2011), America (McEvoy et al., 2012; Quiring and Papakryiakou, 2003) and Asia (Ebrahimpour et al., 2015;Wang et al., 2016a). However, there is no general consensus on the most suitable indices for this purpose (Esfahanian et al., 2017). Despite the existing literature, very few studies (Peña-Gallardo et al., 2018a; Tian et al., 2018) have compared drought indices to identify their appropriateness for monitoring drought impacts on agriculture and for various crop types.

Among Mediterranean countries, agriculture in Spain is particularly sensitive to climate because of the low average precipitation level and its marked interannual variability (Vicente-Serrano, 2006). Spain has been subject to multiple episodes of drought (Domínguez-Castro et al., 2012), with those in the last century being amongst the most severe to have occurred in

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77   Europe (González-Hidalgo et al., 2018; Vicente-Serrano, 2006). In 2017 the agricultural and livestock losses caused by drought

78   were estimated to be at least 3600 million Euros (UPA, 2017), highlighting the need to establish appropriate tools for

79   monitoring drought impacts on crops.

80   Information on crop production is commonly limited in terms of spatial or temporal availability. Recent studies in Spain have

81   analyzed the impact of drought on various crops since the early 21st century at national or provincial scales (Cantelaube et al.,

82   2004; Hernandez-Barrera et al., 2016; Páscoa et al., 2016), but few have used yield data at finer resolution (García-León et al.,

83   2019) . In this study we compared different drought indices using two datasets at different spatial scales: provincial information

84   provided by the national statistical services, and a regional dataset specifically developed for the study. The objectives of this

85   study were: (1) to determine the most appropriate and functional drought index among four Palmer-related drought indices

86   (Palmer drought severity index: PDSI; Palmer hydrological drought index: PHDI; Palmer Z index: Z-index; Palmer modified

87   drought index: PMDI), and the standardized precipitation evapotranspiration index (SPEI), the standardized precipitation index

88   (SPI), and the standardized Palmer drought index (SPDI); (2) to identify the temporal response of two main herbaceous rainfed

89   crops (wheat and barley) to drought; and (3) to determine whether there were common spatial patterns, by comparing the two

90   datasets at different spatial scales.

91   **2. Methods and datasets**

92   **2.1.Crop yield data**

93   The statistical analysis was conducted using an annual dataset of crop yields for peninsular Spain and the Balearic Islands at

94   two spatial scales for the two main herbaceous rainfed crops (barley and wheat). We obtained provincial annual yield data

95   from the National Agricultural Statistics Annuaries published by the Spanish Ministry of Agriculture, Fishing and Environment

96   (MAPA), available at: https://www.mapa.gob.es/es/estadistica/temas/publicaciones/anuario-de-estadistica/default.aspx (last

97   accessed: March 2018); these include agricultural statistics since the early 20th century. We used data from 1962 to 2014, to

98   match climate data that was available for this period. The Gipuzkoa and Vizcaya provinces were not used in the analysis at

99   the province scale as wheat has not been cultivated there since 1973 and 1989, respectively. We used crop production data

100   collected by the *Encuesta sobre Superficies y Rendimientos de Cultivos-Survey on surface and crop yields* (Esyrce), an agrarian

101   yield survey undertaken by the MAPA since 1990. This survey records information about crop production at parcel scale every

102   year from a sample of parcels. Yield observations were aggregated to the main spatial unit defined for agricultural districts by

103   the MAPA (Fig. 1). As not all territories were included in this survey until 1993, we only considered the period 1993–2015.

104   Data on barley production is limited in the Esyrce database, and the agricultural districts considered in this study did not

105   correspond to all the areas where this crop is cultivated.

106   For both datasets the unit of measure was the harvested production per unit of harvested area (kg/ha); it did not include any

107   measure of production related to the area of the crop planted in each province or region. To consider the total area covered by

108   the crops we used the defined rainfed crop delimited area for Spain, derived from the Corine land cover 2000 database

109   (http://centrodedescargas.cnig.es/CentroDescargas/catalogo.do?Serie=MPPIF ; last accessed: March 2018).

110   The spatial resolution of yield data can influence the interpretation of drought impacts on agriculture. Figure 2 shows a

111   comparison of crop yields for the common period of available information in both datasets (1993–2014). Overall, the average

112   production was greater at the agricultural district scale than at the provincial scale. Tables S1 and S2 summarize the

113   relationships between the datasets for each province for the available common period, based on Pearson's correlations

114   coefficients for wheat and barley yields, respectively. It was surprising that both datasets showed very different temporal

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115   variability in crop yields in the analyzed provinces. Wheat yields showed good agreement and highly significant correlations

116   between both datasets in provinces including Ávila (r = 0.77), Barcelona (r = 0.69), Burgos (r = 0.82), Cuenca (r = 0.86),

117   Guadalajara (r = 0.87), León (r = 0.69), Palencia (r = 0.73), Salamanca (r = 0.87), Segovia (r = 0.94), Teruel (r = 0.83),

118   Valladolid (r = 0.92), and Zamora (r = 0.75), while in other provinces including Castellón, Málaga, Murcia, and Navarra the

119   correlations were non significant or negative. Thus, the national statistics for these districts were unreliable. For barley yields

120   the available regional data were more limited, but similar relationships with good agreement and more highly significant

121   correlations were found among the datasets for the provinces where wheat was also cultivated, including Cáceres (r = 0.48),

122   Cuenca (r = 0.88), Granada (r = 0.51), Guadalajara (r = 0.86), La Rioja (r = 0.76), and Tarragona (r = 0.88); however, for

123   Sevilla the correlation was negative and significant (r = −0.35).

124   Mechanization and innovation in agriculture have increased since last century, resulting in a trend of increased yields (Lobell

125   and Field, 2007), that is also evident in data for Spain. To remove bias introduced by non-climate factors, and to enable

126   comparison of yields between the two crop types, the original series were transformed to standardized yield residuals series

127   (SYR), using the following quadratic polynomial equation:

128
$$SYRS = \frac{y_{d-\mu}}{\sigma}$$

129   where y_d is the residuals of the de-trended yield obtained by fitting a linear regression model, μ is the mean of the de-trended

130   series, and σ is the standard deviation of the de-trended yield.

131   This methodology has been applied in other similar studies (Chen et al., 2016; Potopová et al., 2015; Tian et al., 2018). the

132   full procedure is described by Lobell and Asner, (2003), Lobell et al., (2011) and Potopová et al., (2015).

133   **2.2. Climate data**

134   We used a weekly gridded dataset of meteorological variables (precipitation, maximum and minimum temperature, relative

135   humidity and sunshine duration) at 1.1 km resolution for peninsular Spain and the Balearic Islands for the period 1962–2015.

136   The grids were generated from a daily meteorological dataset provided by the Spanish National Meteorological Agency

137   (AEMET), following quality control and homogenization of the data. Further details on the method and the gridding procedure

138   are provided by Vicente-Serrano et al., (2017). Reference evapotranspiration (ETo) was calculated using the FAO-56 Penman-

139   Monteith equation (Allen et al., 1998). Weekly data were aggregated at the monthly scale for calculation of the various drought

140   indices**.**

141   **2.3. Methods**

142   **2.3.1.   Drought indices**

143   **Palmer Drought Severity Indices (PDSIs)**

144   Palmer (1965) developed the Palmer drought severity index (PDSI). Variations of this index include the Palmer hydrological

145   drought index (PHDI), the Palmer moisture anomaly index (Z-index), and the Palmer modified drought index (PMDI).

146   Computation of the Palmer indices (PDSIs) is mainly based on estimation of the ratio between the surface moisture and the

147   atmospheric humidity demand. Subsequent studies have revealed that spatial comparison among regions is problematic (Alley,

148   1984; Doesken and Garen, 1991; Heim, 2002). In this context we followed the variation introduced by Wells et al., (2004);

149   this enables spatial comparison when determining a suitable regional coefficient, developing the self-calibrated PDSIs. PDSIs

150   are also referred to as uni-scalar indices, which can only be calculated at fixed and unknown timescales (Guttman, 1998;
151   Vicente-Serrano et al., 2010); this is a limitation of these indices.

Standardized Precipitation Index (SPI)

153   The standardized precipitation index (SPI) was introduced by Mckee et al. (1993), and provided a new approach to the
154   quantification of drought at multiple time scales. The index is based on the conversion of precipitation series to a standard
155   normal variable having a mean equal to 0 and variance equal to 1, by adjusting an incomplete Gamma distribution. The SPI is
156   a meteorological index used worldwide, and is especially recommended by The World Meteorological Organization (WMO,
157   2012) for drought monitoring and early warning.

Standardized Precipitation Evapotranspiration Index (SPEI)

159   Vicente-Serrano et al. (2010) proposed the standardized precipitation evapotranspiration index (SPEI) as a drought index that
160   takes into consideration the effect of atmospheric evaporative demand on drought severity. It provides monthly climate
161   balances (precipitation minus reference evapotranspiration), and the values are transformed to normal standardized units using
162   a 3-parameter log-logistic distribution. Following the concept of the SPI, the SPEI enables comparison of drought
163   characteristics at various time scales among regions, independently of their climatic conditions. The SPEI has been widely
164   used in drought-related studies, including to investigate the impacts of drought on various crops worldwide (Chen et al., 2016;
165   Kuhnert et al., 2016; Peña-Gallardo et al., 2018b; Potopová et al., 2016b; Vicente-Serrano et al., 2012).

Standardized Precipitation Drought Index (SPDI)

167   The standardized precipitation drought index (SPDI) was developed by Ma et al (2014), and relies on the concept of time
168   scales. It is considered to be a combined version of the PDSI and the SPEI, because the SPDI accumulates the internal water
169   valance anomalies (D) obtained in the PDSI scheme at various time scales, and the values are later transformed into z-units
170   following a standard normal distribution. For this purpose a log-logistic distribution has been used, because this has been
171   shown to be effective at the global scale (Vicente-Serrano et al., 2015).

172   The SPEI, SPI, and SPDI are referred to here as multi-scalar indices, and the PDSIs as uni-scalar indices. Thus, the multi-
173   scalar indices were computed at scales of 1, 12, 18, and 24 months, and along with the PDSIs series were de-trended by
174   adjusting a linear regression model to enable accurate comparisons with de-trended crop yield information. Following the
175   same procedure used for the yield series, the residual of each monthly series was summed to the average value for the period.

2.3.2.   Correlation between drought indices and crop yields

177   The relationship between the drought indices and the SYRS for both datasets was assessed by calculating polynomial
178   correlation coefficients (c) (Baten and Frame, 1959). We used a second-order polynomial regression model, given the common
179   nonlinear relationship between drought indices and crop production (Páscoa et al., 2016; Zipper et al., 2016). Hereafter, the
180   references made to correlations refer to results obtained using the polynomial approach. The months of August and September
181   were excluded from the analysis because they correspond to the post harvest period, and we were considering only the period
182   from sowing to harvest.

183   As the month of the year when the greatest correlation between the drought index and the crop yield was not known beforehand,
184   all 10 monthly series for each index were correlated with the annual yield, and the highest correlation value was used. In the
185   case of the multi-scalar indices, for each monthly series and time scale we obtained 10 correlations (one for each of the 10

186 months and the 14 time scales considered in the analysis). Thus, 120 correlations were obtained for each crop and spatial unit

187 considered in the analysis (only correlations significant at $p < 0.05$ were considered). In addition, we used the time scale (in

188 the case of multi-scalar drought indices) and the month in which the strongest correlation was found.

189 A t-test was performed to assess the significance of the differences in the polynomial regression correlation coefficients

190 obtained from the drought–yield relationships, to determine whether there were significant similarities or differences among

191 the indices.

192 **2.4. Identification of spatial patterns for crop yield response to drought.**

193 A principal component analysis (PCA) was performed to identify general patterns in the effect of drought on crop yields, in

194 relation to seasonality of the effects. PCA is a mathematical technique that enables the dimensionality of a large range of

195 variables to be reduced, by fitting linear combinations of variables. We conducted a T-mode analysis, and used the varimax

196 method to rotate the components to obtain more spatially robust patterns (Richman, 1986). The monthly series of the monthly

197 maximum correlation values found from the yield–drought relationship were the variables (one data point per month), and the

198 provinces and agricultural districts were the cases. We selected two principal components (PC) that in combination explained

199 > 60% of the variance (individually the other components explained < 5% of the variance), and aggregated each province or

200 agricultural district according to the maximum loading rule (i.e., assigning each spatial unit to the PC for which the highest

201 loading value was found). The loadings were expressed in the original correlation magnitudes using the matrix of component

202 weights.

203 **3.   Results**

204 **3.1. Relationship of drought indices to crop yields**

205 Figure 3 shows the strongest correlation found between the crop yield for each dataset and the monthly drought indices. The

206 correlations differed substantially between the two groups of indices. Independently of the crop type, month of the year, or the

207 drought time scale considered, the correlation coefficients for the multi-scalar indices were much higher than those for the uni-

208 scalar indices. In both cases weaker correlations were found for the wheat crops compared with the barley crops. The PDSI,

209 PHDI, and PMDI correlations were non significant ($p < 0.05$), but the correlations for the Z-index and the multi-scalar indices

210 were significant for most provinces and agricultural districts. The correlation values for the three multi-scalar drought indices

211 were similar. At district scale the average values were $c = 0.57$ and $c = 0.6$ for wheat and barley, respectively, and $c = 0.41$

212 and $c = 0.48$ at the provincial scale. Thus, the datasets showed a stronger correlation for the drought indices at district scale

213 than at the provincial scale. In addition, more variability was found in the provincial data than in the regional data, associated

214 with the length of the available records.

215 The spatial distribution of the maximum correlation coefficients between the drought indices and the crop yields are shown in

216 figures 4 and 5, for the province and district scales, respectively. The wheat and barley yield–drought correlations showed a

217 similar spatial pattern among indices at the province scale. Stronger correlations ($c \geq 0.7$) were found for the SPEI and SPI for

218 the provinces of Castilla y León (Valladolid, Zamora, Segovia, and Soria), Aragón (Zaragoza and Teruel), Castilla La Mancha

219 (Guadalajara, Albacete, and Toledo), and the province of Valencia (particularly the cereal agricultural districts). The weakest

220 correlations were found for the southern (Andalusian) provinces. For the Palmer drought indices, the PMDI and Z-index

221 showed similar spatial patterns to the multi-scalar indices (especially in the central and northern provinces), but the correlations

222 were weaker ($c = 0.25–0.6$). For most provinces the weakest correlations were found for the PDSI and PHDI ($c = 0.1–0.25$)

223 for both crops, with no clear spatial difference in the correlations.

224 The spatial distribution of correlations between wheat yields and the drought indices at the agricultural district scale showed
225 clearer patterns than those for the province level. Thus, the response of drought indices at district scale is similar to the response
226 observed at provincial scale, showing stronger correlations for the multi-scalar indices and weaker correlations for the Palmer
227 indices, especially the PDSI and PHDI. The distribution of correlations among the multi-scalar indices was very similar. The
228 most correlated agricultural districts (c ≥ 0.8) were in Castilla y León, especially Valladolid, Segovia, north of Ávila, and
229 northeast of Salamanca. Similar correlations were found for areas of northeast Spain. There was a gradient in correlations from
230 north to south, with the exception of some districts in northwestern Málaga, where wheat is extensively cultivated. In addition,
231 in some districts of Galicia, where expansion of the planted wheat area has not been large, there was a strong relationship
232 between drought indices and crop yields. The results for barley suggest a similar spatial relationship for the various drought
233 indices. The highest coefficients were found for the multi-scalar indices, followed by the Z-index and the PMDI, with districts
234 north of Cáceres, north of Galicia, and in Guadalajara showing correlations in the order of c = 0.8, while the correlations were
235 weaker (c = 0.25−0.4) in districts in the south of Córdoba and Jaén.

236 **3.2. Relationship of drought indices to crop yields: temporal responses**

237 Table 1 summarizes the time scales at which the strongest correlations were found for each of the three multi-scalar indices.
238 Strongest correlations were found for short time scales (1−3 months) for both datasets and both crops, in general with little
239 difference between the indices. For wheat, for 52.6% of the agricultural districts the yield was most strongly correlated with
240 all three drought indices at a time scale of 1−3 months; this was also the case for 49.6% of provinces. In agricultural districts
241 where wheat is cultivated the strongest correlations were predominantly at the 1-month scale (20.37%), especially for the
242 SPDI, while for most of the provinces this occurred at the 3-month scale, particular for the SPEI and SPI (23.26%). For barley,
243 57.4% of the districts and 58.7% of provinces where this crop was grown the strongest correlations were predominantly at 1-
244 to 3-month time scales. Among the various indices for districts, the SPI showed the strongest correlation at the 1-month scale,
245 while for provinces the SPEI showed the strongest correlation at the 3-month scale (33.33%).

246 The multi-scalar drought indices showed similar results. Among these, the SPEI was the index most strongly correlated with
247 yield in the highest percentage of provinces and districts (Table 2). For wheat crops the SPEI was the most strongly correlated
248 index with yield in ~37% of the agricultural districts and ~58% of the provinces; these correlations were found predominantly
249 at the 3-month time scale. For this crop the SPDI was most strongly correlated with yield in a similar proportion of districts
250 (~33%), primarily at the 1-month scale, but only ~14% at the province scale. In general, most of the maximum correlations
251 corresponded to short time scales.

252 Figure 6 shows the spatial distribution of the most strongly correlated drought indices. For most of the provinces the SPEI was
253 the index most strongly correlated with crop yield. For the agricultural districts there was substantial spatial variability and,
254 along with the provincial results, no well-defined spatial pattern that distinguished specific areas for which one index was most
255 effective at monitoring drought. For barley the SPDI showed the best correlation with yield among districts (~44%), while in
256 provinces the SPEI was best correlated (~69%). No clear spatial patterns were evident. The similarities in the magnitude of
257 the correlations between multi-scalar drought indices and crop yields were statistically significant. A t-test (Fig. S1) was used
258 to determine whether there were significant differences in the magnitude of correlations obtained using the various multi-
259 scalar drought indices. This showed significant differences between the SPEI and the SPDI in ~30% of agricultural districts
260 where wheat was grown; these were districts that showed a weaker correlation of yield with drought indices. The results
261 suggest that, for districts having strong correlations between drought indices and crop yields, the two indexes were equally
262 useful. A lower proportion of districts where barley is planted showed that statistical differences among indices exist. In

263 contrast, for provinces no significant differences were found. Overall, this suggests the appropriateness of using any of these

264 multi-scalar indices indistinctly.

265

266 **3.3. Spatial patterns of drought index correlations at the monthly scale**

267 Regionalization of the crop yield response to drought based on monthly correlations with the drought indices was undertaken

268 in relation to the most correlated drought index in each region, independently of the month in which this maximum correlation

269 occurred. Thus, in this analysis the results obtained using the various multi-scalar drought indices were merged. General spatial

270 patterns in the effect of drought conditions on yield were identified using a T-mode PCA. Figures 7 and 8 show the results for

271 the provincial and regional datasets, respectively. We selected two components that explained more than the 60% of the

272 variance in each case. This classification reinforced the north−south pattern of correlations previously found for both datasets.

273 Figure 9 shows the time scales for which the maximum monthly correlations were found for the provinces and agricultural

274 districts for each of the defined components, using a maximum loading rule.

275 ### 3.3.1. Wheat

276 *Agricultural district scale*

277 At the district scale the PCA for wheat (Figure 7a) showed more defined spatial patterns than did the PCA at the

278 provincial scale. PC1 explained 43.36% of the variance, and was characterized by stronger correlations ($c = 0.7–0.9$) in districts

279 mainly located on the north and central plateau; these were stronger than those recorded for the same locations at the provincial

280 scale. Weaker correlations ($c = 0.15–0.5$) were dispersed, although these were found predominantly in the south and northwest.

281 The scores for PC1 showed particular sensitivity to drought during spring, although strong correlations were also found during

282 autumn. PC2 explained 18.63% of the variance, and the loading coefficients also showed a clear spatial pattern, with the

283 agricultural districts north of Sevilla and east of Castilla La Mancha having the highest values. The weakest correlations were

284 found for the districts of Andalucía, Extremadura, and Aragón. Lower scores in PC2 characterized the interannual response to

285 drought relative to PC1. These districts in PC2 also showed a stronger response during spring but not autumn, as was found

286 for PC1. The distribution of PCs according to the maximum loading rule enabled identification of a north−south component

287 in the sensitivity of wheat yields to the drought index. The time scales at which wheat yields in agricultural districts responded

288 most during spring varied from shorter time scales (3-month) in districts in PC1 to longer time scales (5- to 6-month) for those

289 in PC2 (Fig. 9e, 9f), which also showed greater variability in most months relative to districts from PC1. Greater variability

290 for wheat at the district scale was observed relative to that at the provincial scale. Due to the major number of observations

291 considered, the response to drought in Spain when considering district scale shows more heterogeneity than at provincial scale.

292 *Provincial scale*

293 The results for wheat at the provincial scale (Fig. 7b) showed that the first (PC1) and second (PC2) components explained

294 51.7% and 20.8% of the variance, respectively. The loadings of the first component were higher for the central plateau and the

295 east of Spain. These represent provinces in the Castilla y León and Castilla y La Mancha districts, and the provinces of

296 Castellón, Valencia, Alicante, Cantabria and Huelva, and Sevilla and Almería in Andalucía. In these provinces there was a

297 strong correlation between drought indices and crop yields, especially during spring, with particularly strong correlations in

298 May. In contrast, during winter the correlations were weaker, especially in February. PC2 showed greater spatial heterogeneity,

299 with strong correlations in the east (Zaragoza and Tarragona provinces) and south (Cádiz, Córdoba, Málaga, Granada, and

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300 Jaén provinces) of Spain. For this component the temporal response to drought was not as strong as that for PC1, but the
301 maximum correlation was also found during May. The distribution of the maximum loadings showed a dispersed pattern, with
302 PC1 grouping provinces in the central plateau and east of Spain, and PC2 grouping those in southern and some northeastern
303 provinces. The averaged temporal response to drought during spring is set at medium time scales (4−7 months). In particular,
304 in May most of the provinces correlated at 5 months (Fig. 9a, 9b), indicating the importance of climatic conditions during
305 winter and spring to the crop yields obtained. This was also evident for the longer time scales at which most of the provinces
306 correlated during the winter months (11−18 months). It is noteworthy that there was great variability in the temporal response
307 of provinces in PC1 in October, February, March, and April.

3.3.2. Barley

Agricultural district *scale*

310 For barley crops (Fig. 8a) both components showed strong correlations (c = 0.6−0.9) in most of the agricultural districts. In
311 general, the districts showing the strongest correlations in PC1 and PC2 were those located in Castilla La Mancha, and north
312 of Cáceres and Córdoba. Scores for PC1 for barley crops were similar to those for PC1 for wheat during spring and autumn,
313 but the results for PC2 suggest that there was little interannual sensitivity to drought. Most of the correlations for spring indicate
314 that barley responded to drought conditions at the 3−4 month scale, mainly in those districts associated with PC1. Barley yields
315 in districts associated with PC2 were more affected by drought conditions in May at 7−9 month time scales (Fig. 9g, 9h).

Provincial scale

317 For barley at the provincial scale (Fig. 8b) we found more variability in the magnitude of correlations. For PC1 (explaining
318 43.22% of the variance) strong correlations (r = 0.7−0.9) were found for the north and central provinces of Castilla y León,
319 the central provinces of Castilla y la Mancha, and Madrid, Teruel, Valencia and Castellón. The provinces associated with PC2
320 (explaining 27.91% of the variance) were more dispersed than those in PC1, and those showing show strong correlations
321 included Zaragoza and Guadalajara in the north, Barcelona and Balearic Islands in the northeast and east, Cáceres in the west,
322 and Cádiz, Córdoba, Málaga, Granada and Jaén in the south. Provinces showing weaker correlations in PC1 were spread in
323 the northeast (e.g., Navarra, Zaragoza, and Lleida) and west of Spain (e.g., Cáceres and Badajoz). Component scores for PC1
324 were higher than for PC2, although for wheat crops both showed maximum scores during spring (March) and minimum scores
325 in autumn and winter. More provinces in May were correlated with drought indices at medium drought time scales (4−8
326 months). During spring, provinces in PC1 showed correlations at longer time scales (7−8 months), while provinces in PC2
327 showed responses at shorter time scales (3−4 months) (Fig. 9c, 9d).

3.3.3. General climatological characteristics for the PCA components

330 Figures S2-11 show the distribution of climatic characteristics including precipitation, atmospheric evaporative demand
331 (AED), maximum and minimum temperature, and the hydroclimatic balance (precipitation minus AED) at the district scale
332 for the two PCA components. For those districts where wheat was cultivated, no major differences in AED values were found
333 among the components. However, minor differences were observed in precipitation among districts belonging to different
334 PCA components. Those in PC2 had on average less precipitation than those in PC1, especially during autumn, but the
335 difference was not substantial. Greater differences were observed for temperature, with PC1 mainly characterized by districts
336 that had higher maximum temperatures in autumn and spring, and with higher minimum temperatures than the districts in PC2.
337 These results highlight the important role of temperature in the different responses of crop yield to drought, and demonstrate

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338   that, contrary to what may have been expected, temperature and not precipitation was the main factor constraining crop growth.

339   Thus, changes in extreme temperature levels may influence future crop yields. Districts in PC2 where the barley yield

340   correlated with drought indices were characterized by lower levels of precipitation and higher maximum and minimum

341   temperatures than districts represented by PC1, and by higher AED, especially from April to July. Extremes of temperature

342   also seemed to be the major factor determining barley crop yield.

343   **4. Discussion**

344   In this study we investigated the impacts of drought on two rainfed crops in Spain, as measured by a variety of drought indices.

345   We used two datasets of annual crop yields, one from agricultural statistics at the provincial scale spanning the period

346   1962–2013, and the other a new database at the agricultural district scale from the available parcel data from the national

347   survey covering the period 1993–2015. To identify the best indicator of the impact of drought on yields and their sensitivity

348   to climate, we evaluated the performance of seven drought indices. The selection of drought indices was based on those

349   commonly used to monitoring droughts worldwide, including the standardized precipitation and evapotranspiration index

350   (SPEI), the standardized precipitation index (SPI), the Palmer drought indices (PDSI, Z-Index, PHDI, and PMDI), and the

351   standardized Palmer drought index (SPDI).

352   Independently of the type of crop and the temporal scale considered, our results showed that drought indices calculated at

353   different time scales (the SPEI, the SPI, and the SPDI) had greater capacity to reflect the impacts of climate on crop yields,

354   relative to uni-scalar drought indices. The better performance of these multi-scalar drought indices was mainly because of their

355   flexibility in reflecting the negative impacts of drought over a range of regions having very different characteristics (Vicente-

356   Serrano et al., 2011). This issue is especially relevant in agriculture, as vegetation components do not respond equally to water

357   deficit. The sensitivity and vulnerability of each type of crop to drought, and the characteristics of the specific region influence

358   the variability evident in the response to droughts (Contreras and Hunink, 2015). Nonetheless, the results of the assessment of

359   the performance of the PDSIs demonstrated that correlations varied markedly among them, showing some exceptions that may

360   affect their usefulness for monitoring purposes. Overall, our results showed that the PHDI had the weakest relationship to crop

361   yields, followed by the PDSI and the PMDI. The better performance of the PDSI over the PHDI was expected, as the latter

362   was primarily developed for hydrological purposes. Likewise, our results confirmed a better performance of the PMDI (a

363   modified version of the PDSI) over the original PDSI for both crops. Our results are consistent with those of previous studies

364   assessing agricultural drought impacts on crop yields at the global (Vicente-Serrano et al., 2012) and regional (Peña-Gallardo

365   et al., 2018b) scales. The Z-index was the best uni-scalar index among the set analyzed in our study. This index measures

366   short-term moisture conditions, which is a major factor in crop stress (Quiring and Papakryiakou, 2003). Thus, the Z-index

367   was more closely correlated with crop yield than any of the other Palmer indices, indicating its usefulness relative to other

368   PDSIs (Karl, 1986).

369   Although our findings point to poorer performance of the Palmer drought indices relative to the multi-scalar drought indices,

370   they remain among the most widely accepted indices. Numerous studies have used the Palmer indices in assessments of the

371   use of drought indices for monitoring agricultural drought in various regions worldwide, and have reported the superiority of

372   the Z-index (Mavromatis, 2007; Quiring and Papakryiakou, 2003; Sun et al., 2012; Tunalıoğlu and Durdu, 2012) ; our results

373   confirm it usefulness among the Palmer drought indices.

374   Nevertheless, it is important to stress that the usefulness of PDSIs is less than drought indices that can be computed at different

375   time scales (Vicente-Serrano et al. 2012). We demonstrated that the three multi-scalar drought indices in our study (SPEI, SPI,

376   and SPDI) were able to detect drought at different time scales, enabling past weather conditions to be related to present

377   conditions in regions characterized by diverse climatic conditions. This is consistent with previous comparative studies in

378   various regions that reported multi-scalar drought indices were effective for monitoring drought impacts on agricultural lands

379   (Blanc, 2012; Kim et al., 2012; Potopová, 2011; Potopová et al., 2016a; Tian et al., 2018; Zhu et al., 2016; Zipper et al., 2016).

380   Although previous studies reported differences among some of the above three indices (e.g., the SPDI and the SPEI; Ghabaei

381   Sough et al., 2018), others have reported similarities in their performance in assessing agricultural drought impacts (Labudová

382   et al., 2016; Peña-Gallardo et al., 2018a). The similar magnitudes of their correlations suggest a similar ability to characterize

383   the impact of drought on crop yields. However, minor differences among these indices suggested the SPEI performed best.

384   First, for both crops slightly stronger correlations were observed with the SPEI, although the SPDI was superior in relation to

385   barley yields at the agricultural district scale. In general, the SPEI was found to be the most suitable drought index in the

386   majority of agricultural districts and provinces. This suggests that inclusion of AED in the drought index calculation, as occurs

387   in the SPEI, provides greater capacity to predict drought impacts on crop yields compared with the use of precipitation only.

388   Variation in the maximum and minimum temperatures has been found to be the major factor differentiating agricultural

389   districts and provinces having greater sensitivity to drought. Previous studies have stressed the risks associated with an increase

390   in global temperatures, particularly maximum temperatures, and the possible effects on crop yields (Lobell and Field, 2007;

391   Moore and Lobell, 2014). Thus, a ~5.4% reduction in grain yields resulting from an increase in average temperature is expected

392   to occur under the current global warming scenario (Asseng et al., 2014; Zhao et al., 2017).

393   The temporal and spatial effects of drought on yields seem to be very complex, given the observed variability in Spain. In this

394   respect, significant yield effects of drought were found in both datasets. Nevertheless, at the agricultural district scale there

395   was a more evident spatial effect of drought on agricultural yields. This is a key finding for spatial-scale analyses, although

396   the lack of long time series datasets on regional yields is a common constraint.

397   Drought effects on barley and wheat were similar in space and time, although their sensitivity to drought differed, as shown

398   by differences in the magnitude of the correlations with the drought indices, with wheat yields showing stronger correlations

399   than barley yields. This can be explained by the different physiological characteristics of the two crops, as barley is less

400   dependent on water availability at germination and the grain filling stage than wheat (Mamnouie et al., 2006). Although the

401   transpiration coefficient for barley is higher, this crop is not as subject as wheat to water stress under drought conditions

402   (Fischer et al., 1998). Our results indicate that the temporal responses of barley and wheat to drought conditions were very

403   similar, despite the fact that in Spain barley is typically cultivated later than wheat, and in soils having poor moisture retention.

404   Therefore, the phenological characteristics of each type of crop determine how drought affects yields. The results showed that

405   temperature had a more important role than precipitation, suggesting that extreme variations in average temperature conditions

406   during the most sensitive growth stages may have a negative impact on crops.

407   Overall, crop yields in Spain tend to respond to short drought time scales (1−3 months). However, the sensitivity of crops to

408   drought is greater during spring at medium (4−6 months) time scales. This highlights that moisture conditions during winter

409   (the period corresponding to planting, and the first growth stages of tillering and stem elongation), are crucial for the successful

410   development of the plants (Çakir, 2004; Moorhead et al., 2015; Wang et al., 2016a, 2016b).

411   We found a stronger response of crops to climatic conditions in provinces and agricultural districts in the central plateau, and

412   unexpectedly a weaker response in southwestern districts. This reflects the inconsistencies reported for the Iberian Peninsula

413   by Páscoa et al., (2016) , who argued that spatial differences can be explained mainly by the differing productivities in the

414   various districts; we noted this for the mainly agrarian areas of peninsular Spain (Castilla y León and Castilla La Mancha),

415   and the characteristically heterogeneity of this territory. In the southwestern agricultural areas, where the precipitation rates

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416   are lower and temperatures higher, the correlations of yield with drought were weaker. This can be attributed to episodes of
417   abnormal extreme temperatures, such as the very low temperatures in early spring or warmer than usual temperatures in winter;
418   these would affect the expected low evapotranspiration rates during the cold season (Fontana et al., 2015; Kolář et al., 2014).
419   A recent study by Hernandez-Barrera et al., (2016) demonstrated that during autumn and spring, precipitation deficit is the
420   most influential climate factor affecting wheat growth, while an increase in the diurnal temperature range causes a reduction
421   in wheat yield. We found no major differences in precipitation among districts belonging to any of the two defined components,
422   but found other differences including in the average maximum and minimum temperatures. These findings highlight the
423   complexity in choosing a useful drought index that encompasses the specificities of each crop, including its sensitivity to
424   moisture and environmental conditions throughout the entire growth cycle, and its seasonality. This underscores the importance
425   of testing and comparing the appropriateness of different drought indices to ensure accurate identification of the multi-temporal
426   impacts of drought on natural systems.

5. Conclusions

428   The main findings of this study are summarized below.

(1)   Assessment of the efficacy of drought indices for monitoring the effect of climate on agricultural yields demonstrated the better performance of multi-scalar indices. The ability to calculate these indices at various time scales enabled drought impacts to be more precisely defined than with the use of indices lacking this characteristic. The multi-scalar drought indices assessed also had fewer computational and data requirements (particularly the SPEI and the SPI), which is a significant consideration when performing analyses based on scarce climate data.

(2)   From a quantitative evaluation of the relationship of drought indices to crop yields we determined that both of the multi-scalar drought indices tested were useful for assessment of agricultural drought in Spain. However, the SPEI had slightly better correlations and is the most highly recommended for the purpose.

(3)   The spatial definition of yield responses to drought was clearer at the district scale, where the finer spatial resolution enabled better definition of the patterns of responses because the climatic variability of each region was better captured at this scale.

(4)   Barley and wheat yields were more vulnerable to drought during spring, both at short (1−3 months) and medium (4−6 months) time scales. Moisture conditions during late autumn and winter also had an impact on the crop yields.

(5)   The strongest relationships between drought indices and crop yields were found for the northern and central agricultural districts. The relationships for the southern districts were weaker because of the difficulty of characterizing drought impacts over the diverse and complex territory involved.

(6)   The climatic and agricultural conditions in Spain are very diverse. The large spatial diversity and complexity of droughts highlights the need to establish accurate and effective indices to monitor the variable evolution of drought in vulnerable agriculture areas. Climate change is likely to lead to yield losses because of increased drought stress on crops, so in this context effective monitoring tools are of utmost importance. The authors consider that further analysis complementing this study may help to unravel the climate mechanisms that influence the spatio-temporal responses of yields to climate in Spain.

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Bibliography

Alcamo, J., Flörke, M. and Märker, M.: Future long-term changes in global water resources driven by socio-economic and climatic changes, Hydrol. Sci. J., 52(2), 247–275, doi:10.1623/hysj.52.2.247, 2007.

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M.: No Title, Crop Evapotranspiration Guidel. Comput. Crop Water Requir., 1998.

Alley, W. M.: The Palmer Drought Severity Index: Limitations and Assumptions, J. Clim. Appl. Meteorol., 23(7), 1100–1109, doi:10.1175/1520-0450(1984)023<1100:TPDSIL>2.0.CO;2, 1984.

Asseng, S., Foster, I. and Turner, N. C.: The impact of temperature variability on wheat yields, Glob. Chang. Biol., 17(2), 997–1012, doi:10.1111/j.1365-2486.2010.02262.x, 2011.

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D., Kimball, B. A., Ottman, M. J., Wall, G. W., White, J. W., Reynolds, M. P., Alderman, P. D., Prasad, P. V. V., Aggarwal, P. K., Anothai, J., Basso, B., Biernath, C., Challinor, A. J., De Sanctis, G., Doltra, J., Fereres, E., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, L. A., Izaurralde, R. C., Jabloun, M., Jones, C. D., Kersebaum, K. C., Koehler, A.-K., Müller, C., Naresh Kumar, S., Nendel, C., O'Leary, G., Olesen, J. E., Palosuo, T., Priesack, E., Eyshi Rezaei, E., Ruane, A. C., Semenov, M. A., Shcherbak, I., Stöckle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Thorburn, P. J., Waha, K., Wang, E., Wallach, D., Wolf, J., Zhao, Z. and Zhu, Y.: Rising temperatures reduce global wheat production, Nat. Clim. Chang., 5(2), 143–147, doi:10.1038/nclimate2470, 2014.

Blanc, E.: The Impact of Climate Change on Crop Yields in Sub-Saharan Africa, Am. J. Clim. Chang., 01(01), 1–13, doi:10.4236/ajcc.2012.11001, 2012.

Çakir, R.: Effect of water stress at different development stages on vegetative and reproductive growth of corn, F. Crop. Res., 89(1), 1–16, doi:10.1016/j.fcr.2004.01.005, 2004.

Cantelaube, P., Terres, J. and Doblas-Reyes, F.: Influence of climate variability on European agriculture-analysis of winter wheat production, Clim. Res., 27(2), 135–144, doi:10.3354/cr027135, 2004.

Capa-Morocho, M., Ines, A. V. M., Baethgen, W. E., Rodríguez-Fonseca, B., Han, E. and Ruiz-Ramos, M.: Crop yield outlooks in the Iberian Peninsula: Connecting seasonal climate forecasts with crop simulation models, Agric. Syst., 149, 75–87, doi:10.1016/J.AGSY.2016.08.008, 2016.

487 Chen, T., Xia, G., Liu, T., Chen, W., Chi, D., Chen, T., Xia, G., Liu, T., Chen, W. and Chi, D.: Assessment of Drought Impact
488 on Main Cereal Crops Using a Standardized Precipitation Evapotranspiration Index in Liaoning Province, China,
489 Sustainability, 8(10), 1069, doi:10.3390/su8101069, 2016.

490 Contreras, S. and Hunink, J. E.: Drought effects on rainfed agriculture using standardized indices: A case study in SE Spain,
491 in Drought: Research and Science-Policy Interfacing., 2015.

492 Dai, A.: Drought under global warming: a review, Wiley Interdiscip. Rev. Clim. Chang., 2(1), 45–65, doi:10.1002/wcc.81,
493 2011.

494 Doesken, N. J. and Garen, D.: Drought monitoring in the Western United States using a surface water supply index. Presented
495 at: 7th Conference on Applied Climatology, Sept. 10-13, 1991 in Salt Lake City, Utah, in Development of a Surface Water
496 Supply Index (SWSI) for the Western United States, 1991, edited by D. of A. S. Fort Collins, CO: Colorado State University,
497 pp. 77–80., 1991.

498 Domínguez-Castro, F., Ribera, P., García-Herrera, R., Vaquero, J. M., Barriendos, M., Cuadrat, J. M. and Moreno, J. M.:
499 Assessing extreme droughts in Spain during 1750–1850 from rogation ceremonies, Clim. Past, 8(2), 705–722, doi:10.5194/cp-
500 8-705-2012, 2012.

501 Ebrahimpour, M., Rahimi, J., Nikkhah, A. and Bazrafshan, J.: Monitoring Agricultural Drought Using the Standardized
502 Effective Precipitation Index, J. Irrig. Drain. Eng., 141(1), 04014044, doi:10.1061/(ASCE)IR.1943-4774.0000771, 2015.

503 Esfahanian, E., Nejadhashemi, A. P., Abouali, M., Adhikari, U., Zhang, Z., Daneshvar, F. and Herman, M. R.: Development
504 and evaluation of a comprehensive drought index, J. Environ. Manage., 185, 31–43, doi:10.1016/j.jenvman.2016.10.050, 2017.

505 European Commission. Agriculture and Rural Development: Commission offers further support to European farmers dealing
506 with droughts [online] Available from: https://ec.europa.eu/info/news/commission-offers-further-support-european-farmers-
507 dealing-droughts-2018-aug-02-0_en (Accessed 26 October 2018), 2018.

508 European Environment Agency (EEA): Climate change, impacts and vulnerability in Europe 2016. An indicator-based report.,
509 Luxembourg., 2017.

510 Fink, A. H., Brücher, T., Krüger, A., Leckebusch, G. C., Pinto, J. G. and Ulbrich, U.: The 2003 European summer heatwaves
511 and drought -synoptic diagnosis and impacts., 2004.

512 Fischer, R. A., Rees, D., Sayre, K. D., Lu, Z.-M., Condon, A. G. and Saavedra, A. L.: Wheat Yield Progress Associated with
513 Higher Stomatal Conductance and Photosynthetic Rate, and Cooler Canopies, Crop Sci., 38(6), 1467,
514 doi:10.2135/cropsci1998.0011183X003800060011x, 1998.

515 Fontana, G., Toreti, A., Ceglar, A. and De Sanctis, G.: Early heat waves over Italy and their impacts on durum wheat yields,
516 Nat. Hazards Earth Syst. Sci., 15(7), 1631–1637, doi:10.5194/nhess-15-1631-2015, 2015.

517 Forzieri, G., Feyen, L., Russo, S., Vousdoukas, M., Alfieri, L., Outten, S., Migliavacca, M., Bianchi, A., Rojas, R. and Cid,
518 A.: Multi-hazard assessment in Europe under climate change, Clim. Change, 137(1–2), 105–119, doi:10.1007/s10584-016-
519 1661-x, 2016.

520 García-Herrera, R., Díaz, J., Trigo, R. M., Luterbacher, J. and Fischer, E. M.: A Review of the European Summer Heat Wave
521 of 2003, Crit. Rev. Environ. Sci. Technol., 40(4), 267–306, doi:10.1080/10643380802238137, 2010.

522   García-León, D., Contreras, S. and Hunink, J.: Comparison of meteorological and satellite-based drought indices as yield

523   predictors of Spanish cereals, Agric. Water Manag., 213, 388–396, doi:10.1016/J.AGWAT.2018.10.030, 2019.

524   Ghabaei Sough, M., Zare Abyaneh, H. and Mosaedi, A.: Assessing a Multivariate Approach Based on Scalogram Analysis for

525   Agricultural Drought Monitoring, Water Resour. Manag., 32(10), 3423–3440, doi:10.1007/s11269-018-1999-0, 2018.

526   Giorgi, F. and Lionello, P.: Climate change projections for the Mediterranean region, Glob. Planet. Change, 63(2–3), 90–104,

527   doi:10.1016/j.gloplacha.2007.09.005, 2008.

528   Guttman, N. B.: Comparing the Palmer Drought Index and The Standardized Precipitation Index, J. Am. Water Resour. Assoc.,

529   34(1), 113–121, doi:10.1111/j.1752-1688.1998.tb05964.x, 1998.

530   Hanjra, M. A. and Qureshi, M. E.: Global water crisis and future food security in an era of climate change, Food Policy, 35(5),

531   365–377, doi:10.1016/J.FOODPOL.2010.05.006, 2010.

532   Heim, R. R.: A Review of Twentieth-Century Drought Indices Used in the United States, Bull. Am. Meteorol. Soc., 83(8),

533   1149–1165, doi:10.1175/1520-0477(2002)083<1149:AROTDI>2.3.CO;2, 2002.

534   Hernandez-Barrera, S., Rodriguez-Puebla, C. and Challinor, A. J.: Effects of diurnal temperature range and drought on wheat

535   yield in Spain, Theor. Appl. Climatol., doi:10.1007/s00704-016-1779-9, 2016.

536   IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment

537   Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S.

538   Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow,

539   T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

540   Karl, T. R.: The Sensitivity of the Palmer Drought Severity Index and Palmer's Z-Index to their Calibration Coefficients

541   Including Potential Evapotranspiration, J. Clim. Appl. Meteorol., 25(1), 77–86, doi:10.1175/1520-

542   0450(1986)025<0077:TSOTPD>2.0.CO;2, 1986.

543   Kim, B.-S., Sung, J.-H., Kang, H.-S. and Cho, C.-H.: Assessment of Drought Severity over South Korea using Standardized

544   Precipitation Evapo-transpiration Index (SPEI), J. Korea Water Resour. Assoc., 45(9), 887–900,

545   doi:10.3741/JKWRA.2012.45.9.887, 2012.

546   Kolář, P., Trnka, M., Brázdil, R. and Hlavinka, P.: Influence of climatic factors on the low yields of spring barley and winter

547   wheat in Southern Moravia (Czech Republic) during the 1961–2007 period, Theor. Appl. Climatol., 117(3–4), 707–721,

548   doi:10.1007/s00704-013-1037-3, 2014.

549   Kuhnert, M., Yeluripati, J., Smith, P., Hoffmann, H., van Oijen, M., Constantin, J., Coucheney, E., Dechow, R., Eckersten,

550   H., Gaiser, T., Grosz, B., Haas, E., Kersebaum, K.-C., Kiese, R., Klatt, S., Lewan, E., Nendel, C., Raynal, H., Sosa, C., Specka,

551   X., Teixeira, E., Wang, E., Weihermüller, L., Zhao, G., Zhao, Z., Ogle, S. and Ewert, F.: Impact analysis of climate data

552   aggregation at different spatial scales on simulated net primary productivity for croplands, Eur. J. Agron.,

553   doi:10.1016/j.eja.2016.06.005, 2016.

554   Labudová, L., Labuda, M. and Takáč, J.: Comparison of SPI and SPEI applicability for drought impact assessment on crop

555   production in the Danubian Lowland and the East Slovakian Lowland, Theor. Appl. Climatol., 1–16, doi:10.1007/s00704-016-

556   1870-2, 2016.

Natural Hazards
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557   Liu, B., Asseng, S., Müller, C., Ewert, F., Elliott, J., Lobell, D. B., Martre, P., Ruane, A. C., Wallach, D., Jones, J. W.,
558   Rosenzweig, C., Aggarwal, P. K., Alderman, P. D., Anothai, J., Basso, B., Biernath, C., Cammarano, D., Challinor, A., Deryng,
559   D., Sanctis, G. D., Doltra, J., Fereres, E., Folberth, C., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, L. A., Izaurralde,
560   R. C., Jabloun, M., Jones, C. D., Kersebaum, K. C., Kimball, B. A., Koehler, A.-K., Kumar, S. N., Nendel, C., O'Leary, G. J.,
561   Olesen, J. E., Ottman, M. J., Palosuo, T., Prasad, P. V. V., Priesack, E., Pugh, T. A. M., Reynolds, M., Rezaei, E. E., Rötter,
562   R. P., Schmid, E., Semenov, M. A., Shcherbak, I., Stehfest, E., Stöckle, C. O., Stratonovitch, P., Streck, T., Supit, I., Tao, F.,
563   Thorburn, P., Waha, K., Wall, G. W., Wang, E., White, J. W., Wolf, J., Zhao, Z. and Zhu, Y.: Similar estimates of temperature
564   impacts on global wheat yield by three independent methods, Nat. Clim. Chang., 6(12), 1130–1136,
565   doi:10.1038/nclimate3115, 2016.

566   Lobell, D. B. and Asner, G. P.: Climate and management contributions to recent trends in U.S. agricultural yields., Science
567   (80-.)., 299(5609), 1032, doi:10.1126/science.1078475, 2003.

568   Lobell, D. B. and Field, C. B.: Global scale climate–crop yield relationships and the impacts of recent warming, Environ. Res.
569   Lett., 2(1), 014002, doi:10.1088/1748-9326/2/1/014002, 2007.

570   Lobell, D. B., Schlenker, W. and Costa-Roberts, J.: Climate Trends and Global Crop Production Since 1980, Science (80-).,
571   333(6042), 2011.

572   Loukas, A. and Vasiliades, L.: Probabilistic analysis of drought spatiotemporal characteristics in Thessaly region, Greece, Nat.
573   Hazards Earth Syst. Sci., 4(5/6), 719–731, doi:10.5194/nhess-4-719-2004, 2004.

574   Ma, M., Ren, L., Yuan, F., Jiang, S., Liu, Y., Kong, H. and Gong, L.: A new standardized Palmer drought index for hydro-
575   meteorological use, Hydrol. Process., 28(23), 5645–5661, doi:10.1002/hyp.10063, 2014.

576   Mamnouie, E., Ghazvini, R. F., Esfahany, M. and Nakhoda, B.: The Effects of Water Deficit on Crop Yield and the
577   Physiological Characteristics of Barley (Hordeum vulgare L.) Varieties. [online] Available from:
578   http://jast.modares.ac.ir/article-23-5420-en.pdf (Accessed 24 November 2018), 2006.

579   Mavromatis, T.: Drought index evaluation for assessing future wheat production in Greece, Int. J. Climatol., 27(7), 911–924,
580   doi:10.1002/joc.1444, 2007.

581   McEvoy, D. J., Huntington, J. L., Abatzoglou, J. T., Edwards, L. M., McEvoy, D. J., Huntington, J. L., Abatzoglou, J. T. and
582   Edwards, L. M.: An Evaluation of Multiscalar Drought Indices in Nevada and Eastern California, Earth Interact., 16(18), 1–
583   18, doi:10.1175/2012EI000447.1, 2012.

584   Mckee, T. B., Doesken, N. J. and Kleist, J.: The relationshio of drought frequency and duration to time scales, Eighth Conf.
585   Appl.   Climatol.,   17–22   [online]   Available   from:
586   http://www.droughtmanagement.info/literature/AMS_Relationship_Drought_Frequency_Duration_Time_Scales_1993.pdf
587   (Accessed 30 May 2018), 1993.

588   Meng, Q., Chen, X., Lobell, D. B., Cui, Z., Zhang, Y., Yang, H. and Zhang, F.: Growing sensitivity of maize to water scarcity
589   under climate change, Sci. Rep., 6, 19605, doi:10.1038/srep19605, 2016.

590   Moore, F. C. and Lobell, D. B.: Adaptation potential of European agriculture in response to climate change, Nat. Clim. Chang.,
591   4(7), 610–614, doi:10.1038/nclimate2228, 2014.

592   Moorhead, J. E., Gowda, P. H., Singh, V. P., Porter, D. O., Marek, T. H., Howell, T. A. and Stewart, B. A.: Identifying and

Natural Hazards
and Earth System
Sciences
Discussions
Open Access
EGU

593   Evaluating a Suitable Index for Agricultural Drought Monitoring in the Texas High Plains, JAWRA J. Am. Water Resour.
594   Assoc., 51(3), 807–820, doi:10.1111/jawr.12275, 2015.

595   Palmer, W. C.: Meteorological Drought. Research Paper No. 45, 1965, 58 p., U.S. Dep. Commer. Weather Bur. Washington,
596   DC., Research P, 1965.

597   Páscoa, P., Gouveia, C. M., Russo, A. and Trigo, R. M.: The role of drought on wheat yield interannual variability in the
598   Iberian Peninsula from 1929 to 2012, Int. J. Biometeorol., 1–13, doi:10.1007/s00484-016-1224-x, 2016.

599   Peña-Gallardo, M., Vicente-Serrano, S., Domínguez-Castro, F., Quiring, S., Svoboda, M., Beguería, S. and Hannaford, J.:
600   Effectiveness of drought indices in identifying impacts on major crops across the USA, Clim. Res., 75(3), 221–240,
601   doi:10.3354/cr01519, 2018a.

602   Peña-Gallardo, M., Quiring, S., Svoboda, M., Hannaford, J., Tomas-Burguera, M., Martín-Hernández, N., Domínguez-Castro,
603   F. and El Kenawy, A.: Response of crop yield to different time-scales of drought in the United States: Spatio-temporal patterns
604   and climatic and environmental drivers, Agric. For. Meteorol., 264, 40–55, doi:10.1016/j.agrformet.2018.09.019, 2018b.

605   Potopová, V.: Evolution of drought severity and its impact on corn in the Republic of Moldova, Theor. Appl. Climatol., 105(3–
606   4), 469–483, doi:10.1007/s00704-011-0403-2, 2011.

607   Potopová, V., Štěpánek, P., Možný, M., Türkott, L. and Soukup, J.: Performance of the standardised precipitation
608   evapotranspiration index at various lags for agricultural drought risk assessment in the Czech Republic, Agric. For. Meteorol.,
609   202, 26–38, doi:10.1016/J.AGRFORMET.2014.11.022, 2015.

610   Potopová, V., Štěpánek, P., Farda, A., Türkott, L., Zahradníček, P. and Soukup, J.: Drought stress impact on vegetable crop
611   yields in the Elbe River lowland between 1961 and 2014, Cuad. Investig. Geográfica, 42(1), 127, doi:10.18172/cig.2924,
612   2016a.

613   Potopová, V., Boroneanţ, C., Boincean, B. and Soukup, J.: Impact of agricultural drought on main crop yields in the Republic
614   of Moldova, Int. J. Climatol., 36(4), 2063–2082, doi:10.1002/joc.4481, 2016b.

615   Quiring, S. M. and Papakryiakou, T. N.: An evaluation of agricultural drought indices for the Canadian prairies, Agric. For.
616   Meteorol., 118(1), 49–62, doi:10.1016/S0168-1923(03)00072-8, 2003.

617   Richman, M. B.: Rotation of principal components, J. Climatol., 6(3), 293–335, doi:10.1002/joc.3370060305, 1986.

618   Sepulcre-Canto, G., Horion, S., Singleton, A., Carrao, H. and Vogt, J.: Development of a Combined Drought Indicator to
619   detect agricultural drought in Europe, Nat. Hazards Earth Syst. Sci., 12(11), 3519–3531, doi:10.5194/nhess-12-3519-2012,
620   2012.

621   Spinoni, J., Vogt, J. V., Naumann, G., Barbosa, P. and Dosio, A.: Will drought events become more frequent and severe in
622   Europe?, Int. J. Climatol., 38(4), 1718–1736, doi:10.1002/joc.5291, 2018.

623   Sun, L., Mitchell, S. W. and Davidson, A.: Multiple drought indices for agricultural drought risk assessment on the Canadian
624   prairies, Int. J. Climatol., 32(11), 1628–1639, doi:10.1002/joc.2385, 2012.

625   Tack, J., Barkley, A. and Nalley, L. L.: Effect of warming temperatures on US wheat yields., Proc. Natl. Acad. Sci. U. S. A.,
626   112(22), 6931–6, doi:10.1073/pnas.1415181112, 2015.

627   Tian, L., Yuan, S. and Quiring, S. M.: Evaluation of six indices for monitoring agricultural drought in the south-central United

628   States, Agric. For. Meteorol., 249, 107–119, doi:10.1016/J.AGRFORMET.2017.11.024, 2018.

629   Tsakiris, G. and Tigkas, D.: Drought Risk in Agriculture in Mediterranean Regions. Case Study: Eastern Crete, in Methods

630   and Tools for Drought Analysis and Management, pp. 399–414, Springer Netherlands, Dordrecht., 2007.

631   Tunalıoğlu, R. and Durdu, Ö. F.: Assessment of future olive crop yield by a comparative evaluation of drought indices: a case

632   study in western Turkey, Theor. Appl. Climatol., 108(3–4), 397–410, doi:10.1007/s00704-011-0535-4, 2012.

633   UPA, Unión de Pequeños Agricultores y Ganaderos: La sequía y sus efectos sobre la agricultura y la ganadería, [online]

634   Available from: https://www.upa.es/upa/uControlador/index.php?nodo=1021&hn=2232 (Accessed 25 October 2018), 2017.

635   Vergni, L. and Todisco, F.: Spatio-temporal variability of precipitation, temperature and agricultural drought indices in Central

636   Italy, Agric. For. Meteorol., 151(3), 301–313, doi:10.1016/j.agrformet.2010.11.005, 2011.

637   Vicente-Serrano, S. M.: Spatial and temporal analysis of droughts in the Iberian Peninsula (1910–2000), Hydrol. Sci. J., 51(1),

638   83–97, doi:10.1623/hysj.51.1.83, 2006.

639   Vicente-Serrano, S. M., Beguería, S., López-Moreno, J. I., Vicente-Serrano, S. M., Beguería, S. and López-Moreno, J. I.: A

640   Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index, J. Clim.,

641   23(7), 1696–1718, doi:10.1175/2009JCLI2909.1, 2010.

642   Vicente-Serrano, S. M., Beguería, S. and López-Moreno, J. I.: Comment on "Characteristics and trends in various forms of

643   the Palmer Drought Severity Index (PDSI) during 1900–2008" by Aiguo Dai, J. Geophys. Res., 116(D19), D19112,

644   doi:10.1029/2011JD016410, 2011.

645   Vicente-Serrano, S. M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J. J., López-Moreno, J. I., Azorin-Molina, C., Revuelto,

646   J., Morán-Tejeda, E., Sanchez-Lorenzo, A., Vicente-Serrano, S. M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J. J., López-

647   Moreno, J. I., Azorin-Molina, C., Revuelto, J., Morán-Tejeda, E. and Sanchez-Lorenzo, A.: Performance of Drought Indices

648   for   Ecological,   Agricultural,   and   Hydrological   Applications,   http://dx.doi.org/10.1175/2012EI000434.1,

649   doi:10.1175/2012EI000434.1, 2012.

650   Vicente-Serrano, S. M., Lopez-Moreno, J.-I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J. M.,

651   Azorin-Molina, C., Morán-Tejeda, E., Revuelto, J., Trigo, R., Coelho, F. and Espejo, F.: Evidence of increasing drought

652   severity caused by temperature rise in southern Europe, Environ. Res. Lett. Environ. Res. Lett, 9, 44001–9, doi:10.1088/1748-

653   9326/9/4/044001, 2014.

654   Vicente-Serrano, S. M., Van der Schrier, G., Beguería, S., Azorin-Molina, C. and Lopez-Moreno, J.-I.: Contribution of

655   precipitation and reference evapotranspiration to drought indices under different climates, J. Hydrol., 526,

656   doi:10.1016/j.jhydrol.2014.11.025, 2015.

657   Vicente-Serrano, S. M., Camarero, J. J., Olano, J. M., Martín-Hernández, N., Peña-Gallardo, M., Tomás-Burguera, M., Gazol,

658   A., Azorin-Molina, C., Bhuyan, U. and El Kenawy, A.: Diverse relationships between forest growth and the Normalized

659   Difference Vegetation Index at a global scale, Remote Sens. Environ., 187, doi:10.1016/j.rse.2016.10.001, 2016.

660   Vicente-Serrano, S. M., Tomas-Burguera, M., Beguería, S., Reig, F., Latorre, B., Peña-Gallardo, M., Luna, M. Y., Morata, A.

661   and   González-Hidalgo, J. C.: A High Resolution Dataset of Drought Indices for Spain, Data, 2(3), 22,

662   doi:10.3390/data2030022, 2017.

663   Wang, H., Vicente-serrano, S. M., Tao, F., Zhang, X., Wang, P., Zhang, C., Chen, Y., Zhu, D. and Kenawy, A. El: Monitoring
664   winter wheat drought threat in Northern China using multiple climate-based drought indices and soil moisture during 2000–
665   2013, Agric. For. Meteorol., 228–229, 1–12, doi:10.1016/j.agrformet.2016.06.004, 2016a.

666   Wang, Q., Wu, J., Li, X., Zhou, H., Yang, J., Geng, G., An, X., Liu, L. and Tang, Z.: A comprehensively quantitative method
667   of evaluating the impact of drought on crop yield using daily multi-scale SPEI and crop growth process model, Int. J.
668   Biometeorol., 1–15, doi:10.1007/s00484-016-1246-4, 2016b.

669   Webber, H., Ewert, F., Olesen, J. E., Müller, C., Fronzek, S., Ruane, A. C., Bourgault, M., Martre, P., Ababaei, B., Bindi, M.,
670   Ferrise, R., Finger, R., Fodor, N., Gabaldón-Leal, C., Gaiser, T., Jabloun, M., Kersebaum, K.-C., Lizaso, J. I., Lorite, I. J.,
671   Manceau, L., Moriondo, M., Nendel, C., Rodríguez, A., Ruiz-Ramos, M., Semenov, M. A., Siebert, S., Stella, T.,
672   Stratonovitch, P., Trombi, G. and Wallach, D.: Diverging importance of drought stress for maize and winter wheat in Europe,
673   Nat. Commun., 9(1), 4249, doi:10.1038/s41467-018-06525-2, 2018.

674   Wells, N., Goddard, S., Hayes, M. J., Wells, N., Goddard, S. and Hayes, M. J.: A Self-Calibrating Palmer Drought Severity
675   Index, J. Clim., 17(12), 2335–2351, doi:10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO;2, 2004.

676   Wigley, T. M. L.: The effect of changing climate on the frequency of absolute extreme events, Clim. Change, 97(1–2), 67–76,
677   doi:10.1007/s10584-009-9654-7, 2009.

678   WMO: Standardized Precipitation Index User Guide, 2012.

679   World Bank: World Bank Data. Agriculture, forestry, and fishing, value added (% of GDP) | Data, [online] Available from:
680   https://data.worldbank.org/indicator/nv.agr.totl.zs (Accessed 25 October 2018), 2017.

681   Zargar, A., Sadiq, R., Naser, B. and Khan, F. I.: A review of drought indices, Environ. Rev., 19(NA), 333–349,
682   doi:10.1139/a11-013, 2011.

683   Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.-L., Elliott,
684   J., Ewert, F., Janssens, I. A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., Peng, S., Peñuelas, J., Ruane, A. C., Wallach, D.,
685   Wang, T., Wu, D., Liu, Z., Zhu, Y., Zhu, Z. and Asseng, S.: Temperature increase reduces global yields of major crops in four
686   independent estimates., Proc. Natl. Acad. Sci. U. S. A., 114(35), 9326–9331, doi:10.1073/pnas.1701762114, 2017.

687   Zhu, Y., Wang, W., Singh, V. P. and Liu, Y.: Combined use of meteorological drought indices at multi-time scales for
688   improving hydrological drought detection, Sci. Total Environ., 571, 1058–1068, doi:10.1016/J.SCITOTENV.2016.07.096,
689   2016.

690   Zipper, S. C., Qiu, J. and Kucharik, C. J.: Drought effects on US maize and soybean production: spatiotemporal patterns and
691   historical changes, Environ. Res. Lett., 11(9), 094021, doi:10.1088/1748-9326/11/9/094021, 2016.

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Tables

Table 1. Percentage of analyzed agricultural districts and provinces where wheat and barley are cultivated, at which the maximum correlations per time scale were found using the multi-scalar indices.

Time-scale		1	2	3	4	5	6	7	8	9	10	11	12	18	24
							a)	Agricultural district data							
Wheat	SPI	18.38	15.38	13.68	9.83	4.27	7.26	2.56	5.13	1.28	3.42	6.41	2.14	5.98	4.27
	SPEI	16.67	14.96	17.09	9.83	6.41	3.42	5.13	4.7	3.42	2.56	3.85	4.27	5.13	2.56
	SPDI	26.07	21.79	13.68	5.13	3.42	2.99	2.56	2.56	2.14	5.13	1.71	3.85	3.42	5.56
Averaged %		**20.37**	**17.38**	**14.82**	**8.26**	**4.70**	**4.56**	**3.42**	**4.13**	**2.28**	**3.70**	**3.99**	**3.42**	**4.84**	**4.13**
Barley	SPI	29.63	14.81	14.81	12.96	0	3.7	3.7	1.85	3.7	1.85	1.85	3.7	3.7	3.7
	SPEI	24.07	12.96	22.22	9.26	1.85	3.7	5.56	3.7	3.7	1.85	0	5.56	1.85	3.7
	SPDI	24.07	14.81	14.81	7.41	7.41	3.7	11.11	1.85	0	3.7	0	0	3.7	7.41
Averaged %		**25.92**	**14.19**	**17.28**	**9.88**	**3.09**	**3.70**	**6.79**	**2.47**	**2.47**	**2.47**	**0.62**	**3.09**	**3.08**	**4.94**
							b)	Provincial data							
Wheat	SPI	6.98	13.95	23.26	6.98	2.33	6.98	6.98	6.98	6.98	2.33	4.65	4.65	4.65	2.33

SPEI	9.3	11.63	23.26	11.63	9.3	0	6.98	6.98	2.33	2.33	4.65	4.65	4.65	2.33
SPDI	13.95	32.56	13.95	2.33	2.33	4.65	4.65	6.98	2.33	2.33	6.98	2.33	0	6.98
Averaged %	**10.08**	**19.38**	**20.16**	**6.98**	**4.65**	**3.88**	**6.20**	**6.98**	**3.10**	**2.33**	**5.43**	**3.88**	**3.10**	**3.88**
SPI	7.14	19.05	30.95	9.52	4.76	7.14	0	2.38	2.38	0	0	11.9	0	4.76
SPEI (Barley)	11.9	11.9	33.33	7.14	4.76	4.76	7.14	4.76	7.14	0	0	2.38	2.38	2.38
SPDI	9.52	38.1	14.29	4.76	4.76	0	0	7.14	0	0	2.38	4.76	2.38	4.76
Averaged %	**9.52**	**23.02**	**26.19**	**7.14**	**4.76**	**6.35**	**2.38**	**2.38**	**5.55**	**0.00**	**0.79**	**6.35**	**1.59**	**3.97**

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707 Table 2. Percentage of analyzed agricultural districts and provinces where wheat and barley are cultivated, where the maximum correlations with the multi-scalar indices
708 were found. Information in parentheses show the time scale at which the provinces and agricultural districts correlate most and the percentage of the provinces and
709 district.
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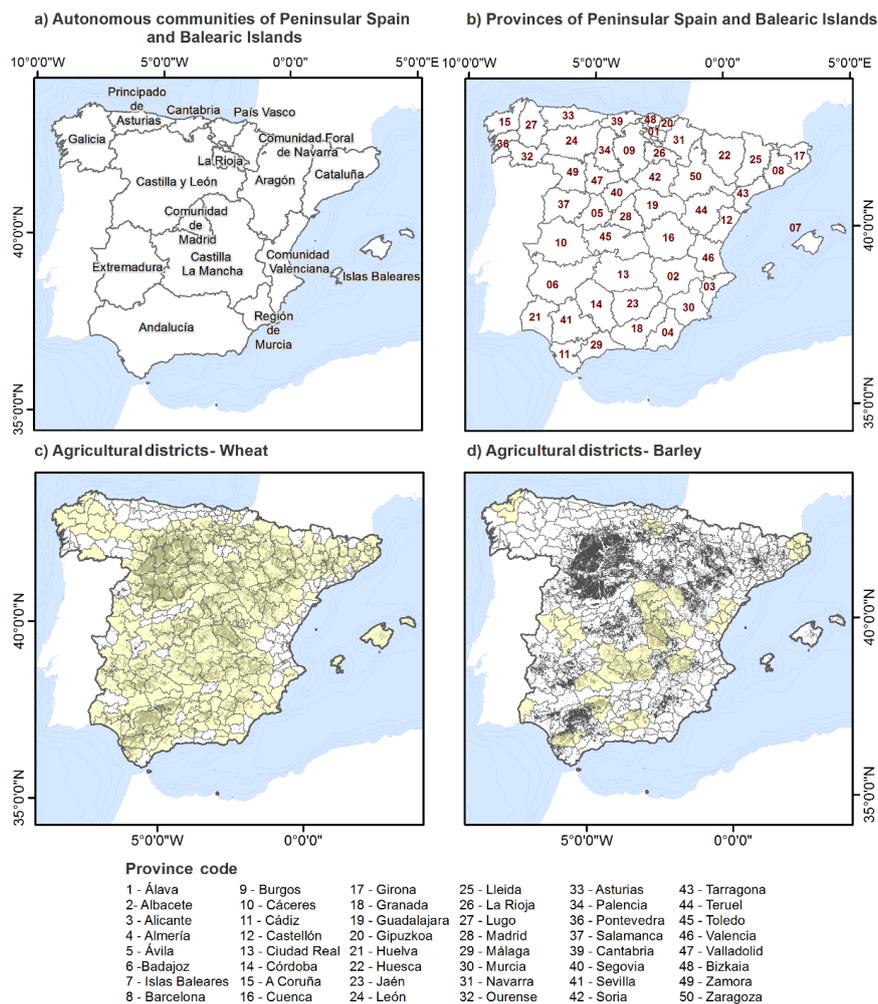|		SPEI	SPDI	SPI
Agricultural districts	**Wheat**	36.75 (3, 7.26)	33.33 (1, 7.69)	29.91 (2, 4.70)
	Barley	35.19 (3, 11.11)	44.44 (1, 12.96)	20.37 (1, 11.11)
Provinces	**Wheat**	58.14 (3, 18.60)	13.95 (24, 4.65)	27.9 (3, 4.65)
	Barley	69.04 (3, 16.66)	9.52 (1, 7.14)	21.42 (5,24, 4.76)

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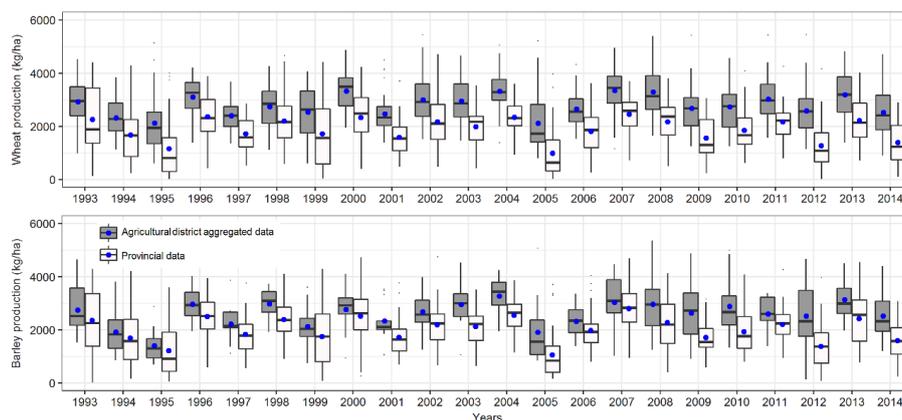713
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Figures


Fig. 1. Location of Spanish Autonomous Communities (a) and provinces (b), and the distribution of agricultural districts having data available (yellow) for wheat (c) and barley (d) yields for the period 1993–2015. Areas where rainfed cereal crops are cultivated (Corine Land Cover 2006) are shown in grey.

Province code

1 - Álava	9 - Burgos	17 - Girona	25 - Lleida	33 - Asturias	43 - Tarragona
2- Albacete	10 - Cáceres	18 - Granada	26 - La Rioja	34 - Palencia	44 - Teruel
3 - Alicante	11 - Cádiz	19 - Guadalajara	27 - Lugo	35 - Málaga	45 - Toledo
4 - Almería	12 - Castellón	20 - Gipuzkoa	28 - Madrid	37 - Salamanca	46 - Valencia
5 - Ávila	13 - Ciudad Real	21 - Huelva	29 - Málaga	38 - Segovia	47 - Valladolid
6 -Badajoz	14 - Córdoba	22 - Huesca	30 - Murcia	40 - Segovia	48 - Bizkaia
7 - Islas Baleares	15 - A Coruña	23 - Jaén	31 - Navarra	41 - Sevilla	49 - Zamora
8 - Barcelona	16 - Cuenca	24 - León	32 - Ourense	42 - Soria	50 - Zaragoza

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Fig. 2. Temporal series of wheat (top) and barley (bottom) yields for the provincial data, and the aggregated
agricultural district data at the province scale for the common period 1993−2014. The solid black line shows
the median and the blue dot shows the mean.

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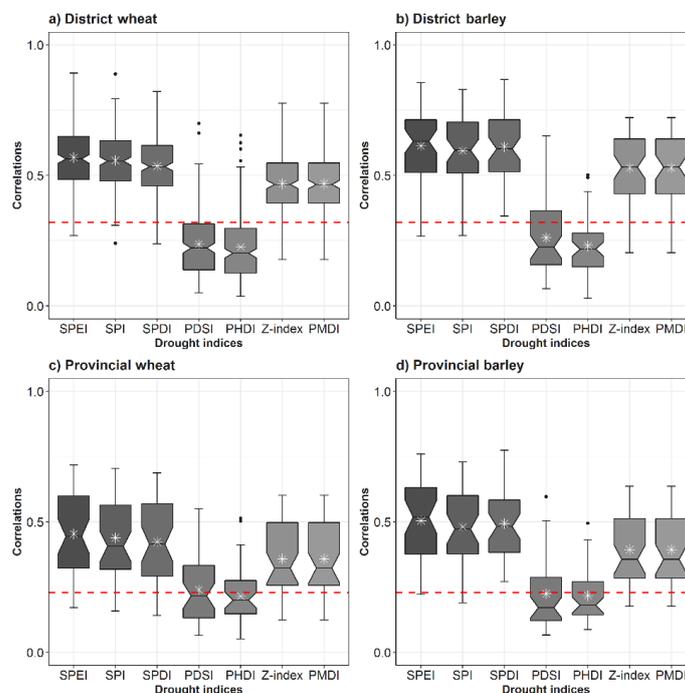
Fig. 3. Box plots showing the strongest correlation coefficients found between drought indices and wheat
and barley yields at the agricultural district (a and b) and provincial (c and d) scales, respectively. The solid
black line shows the median, the white asterisk shows the mean, and the dashed red lines show the $p < 0.05$
significance level.

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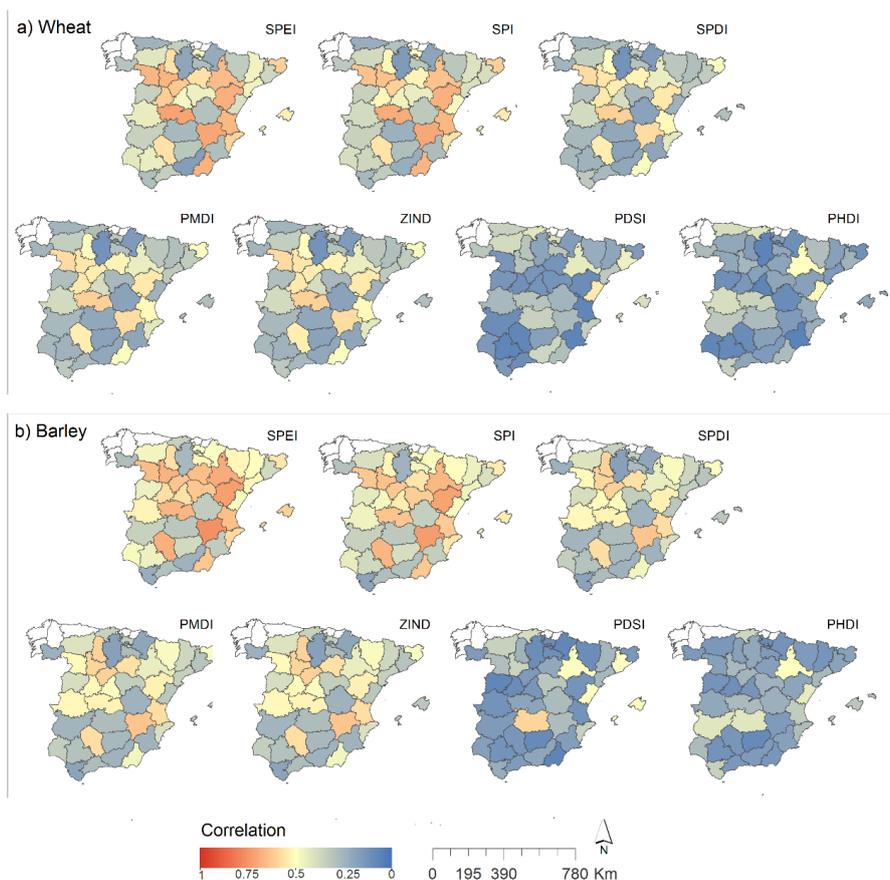
Fig. 4. Spatial distribution of the highest correlation coefficients between the drought indices and the wheat

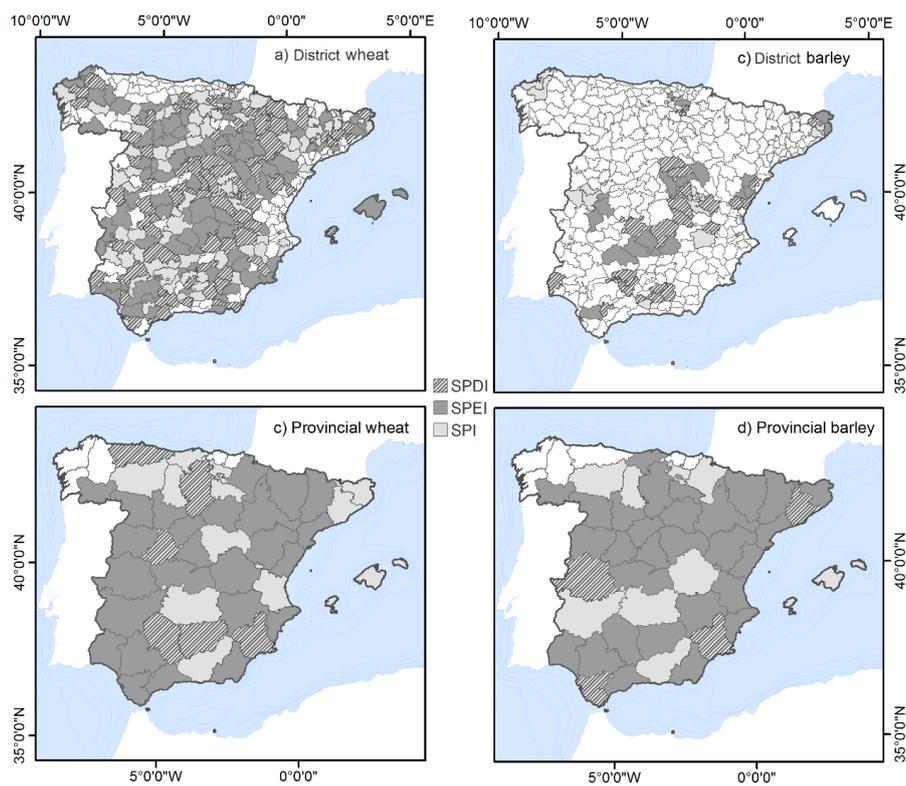(a) and barley (b) yields at the provincial scale, independently of the time scale.

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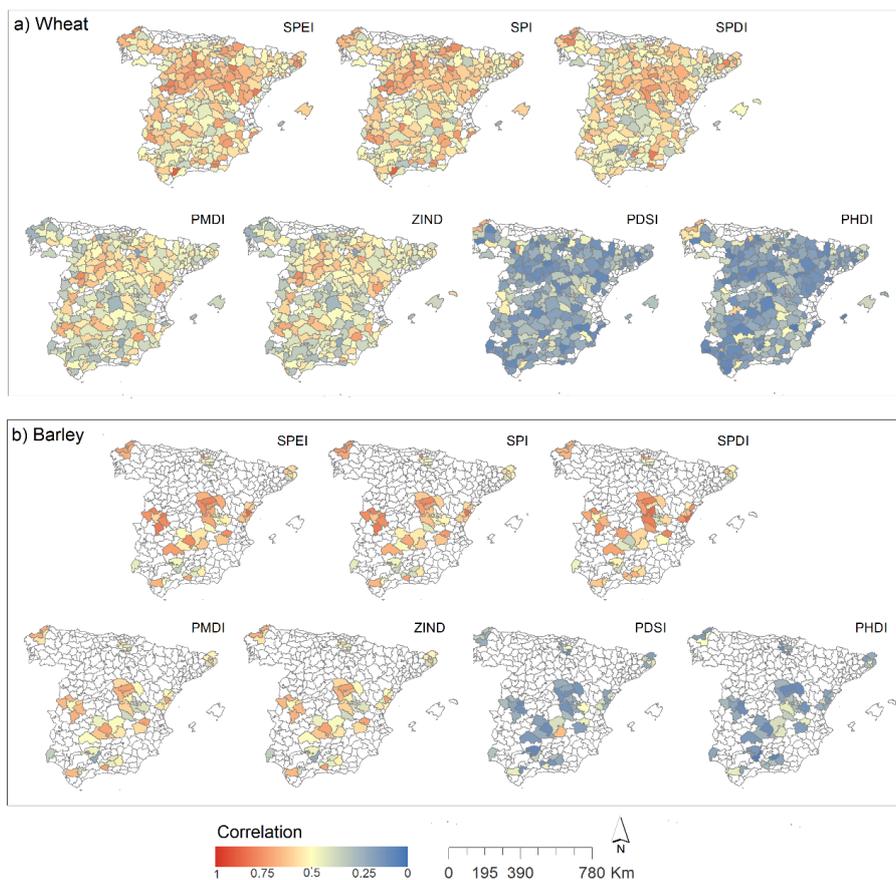
737   Fig. 5. Spatial distribution of the highest correlation coefficients between the drought indices and the wheat

738   (a) and barley (b) yields at the agricultural district scale, independently of the time scale.

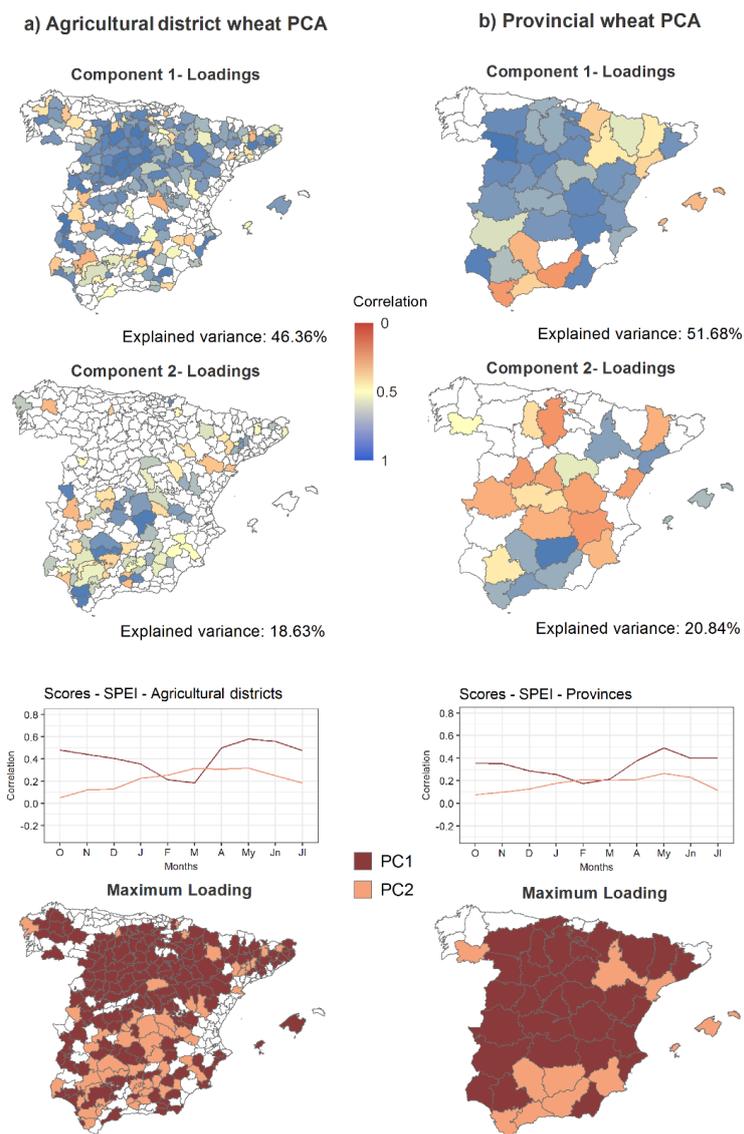Natural Hazards
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740 Fig. 6. Spatial distribution of the drought indices having the strongest correlations with wheat (left) and
741 barley (right) at the province (bottom) and agricultural district (top) scales.

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Fig. 7. PC loadings, PC scores, time scales, and maximum loading rules from the PCA for monthly
maximum correlation coefficients between the SPEI and wheat yields at the agricultural district (a) and
provincial (b) scales, independently of the time scale. The PC loadings and maximum loadings were
significant at $p < 0.05$.

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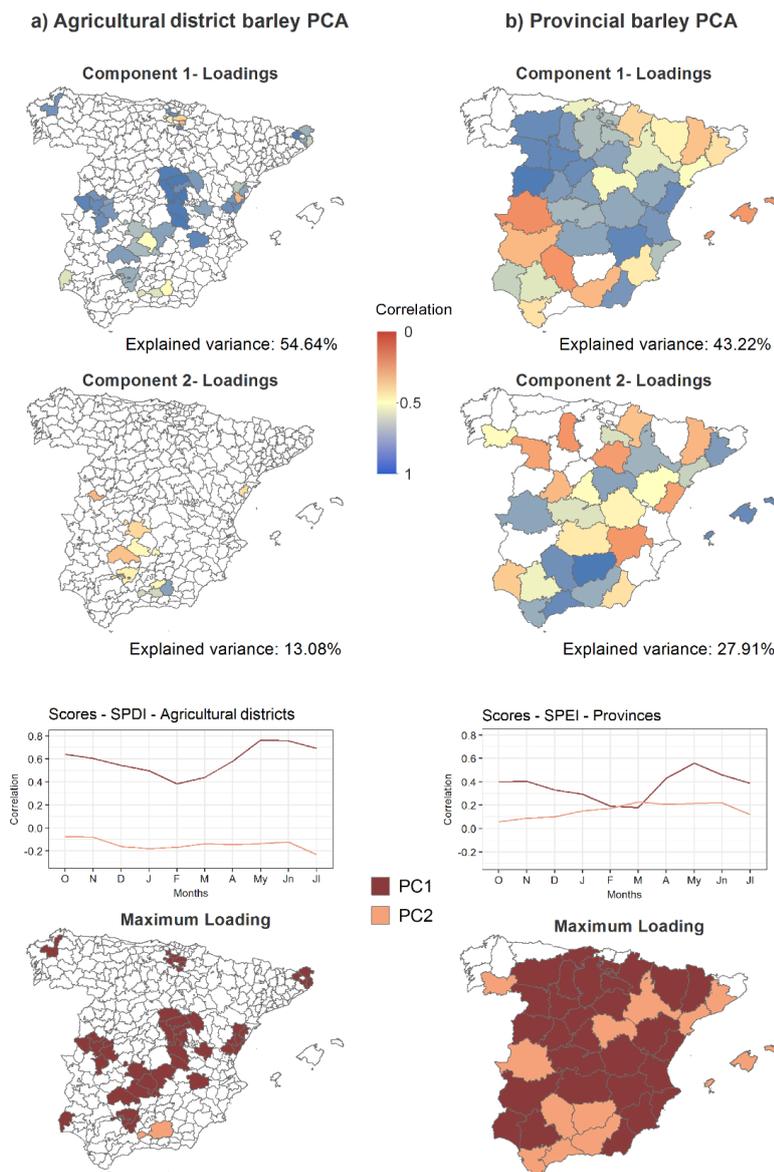
Fig 8. PC loadings, PC scores, time scales, and maximum loading rules from the PCA for monthly maximum correlation coefficients between the SPEI and barley yields at the agricultural district scale (a), and the SPDI and barley yields at the provincial scale (b), independently of the time scale. The PC loadings and maximum loadings were significant at $p < 0.05$.
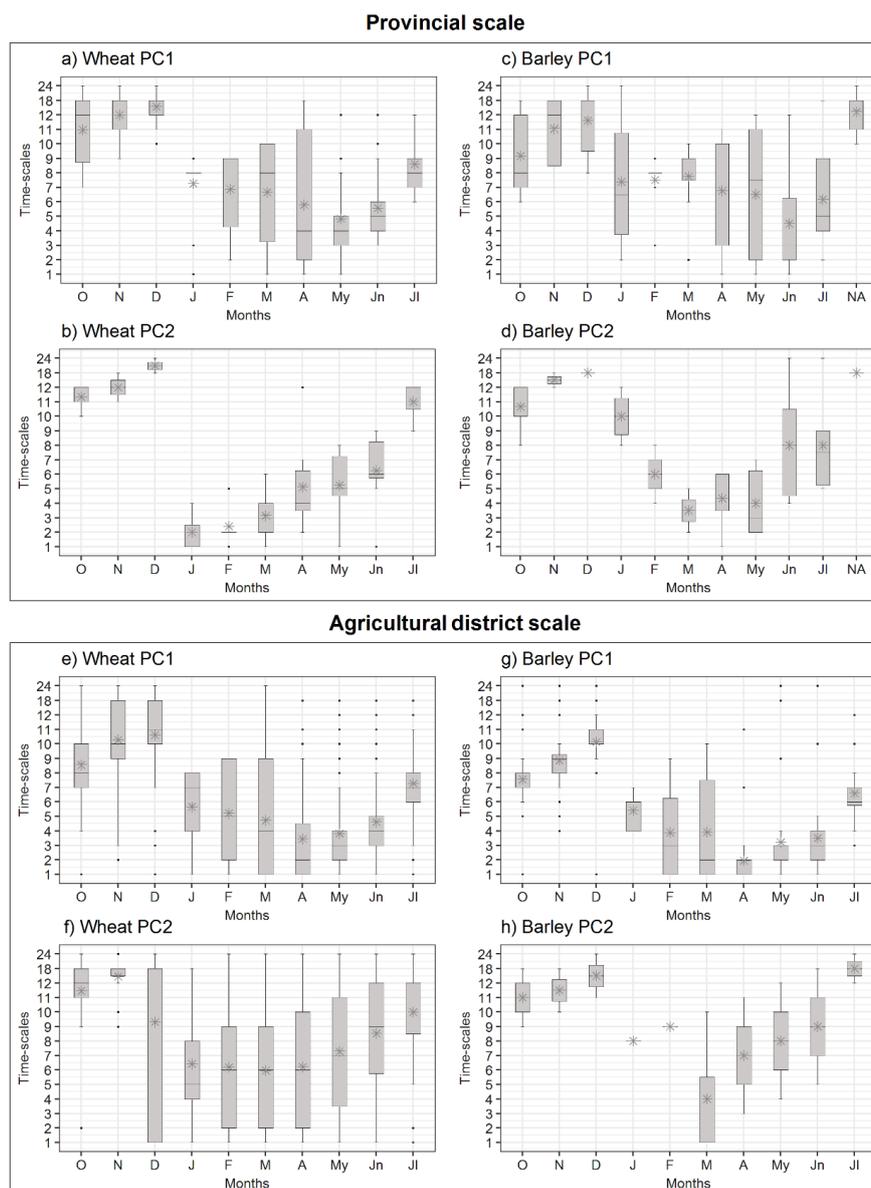
Fig. 9. Box plots showing the time scale at which significant monthly correlations were found in the provinces (top) and agricultural districts (bottom) for wheat and barley for each of the components defined in the PCA.