The predictability of reported drought events and impacts in the Ebro Basin using six different remote sensing data sets

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Abstract. The implementation of drought management plans contributes to reduce the wide range of adverse impacts caused by water shortage. A crucial element of the development of drought management plans is the selection of appropriate indicators and their associated thresholds to detect drought events and monitor the evolution. Drought indicators should be able to detect emerging drought processes that will lead to impacts with sufficient anticipation to allow measures to be undertaken effectively.

5   However, in the selection of appropriate drought indicators the connection to the final impacts is often disregarded. This paper explores the utility of remotely sensed data sets to detect early stages of drought at the river basin scale, and how much time can be gained to inform operational land and water management practices. Six different remote sensing data sets with different spectral origin and measurement frequency are considered, complemented by a group of classical in situ hydrologic indicators. Their predictive power to detect past drought events is tested in the Ebro basin. Qualitative (binary information

10   based on media records) and quantitative (crop yields) data of drought events and impacts spanning a period of 12 years are used as a benchmark in the analysis. Results show that early signs of drought impacts can be detected up to some 6 months before impacts are reported in newspapers, with the best correlation-anticipation relationships for the Standard Precipitation Index (SPI), the Normalized Difference Vegetation Index (NDVI) and Evapotranspiration (ET). Soil Moisture (SM) and Land Surface Temperature (LST) offer also good anticipation, but with weaker correlations, while Gross Primary Production (GPP)

15   presents moderate positive correlations only for some of the rainfed areas. Although classical hydrological information from water levels and water flows provided better anticipation than remote sensing indicators in most of the areas, correlations were found to be weaker. The indicators show a consistent behaviour with respect to the different levels of crop yield in rainfed areas among the analysed years, with SPI, NDVI and ET providing again the stronger correlations. Overall, the results confirm remote sensing products' ability to anticipate reported drought impacts and therefore appear as a useful source of information

20   to support drought management decisions.

1   Introduction

Drought is defined as a temporary water shortage in part caused by anomalous climatic conditions but strongly influenced by socio-economic factors (Kallis, 2008). The effects of drought propagate through all human and natural systems that depend on water directly or indirectly producing substantial losses (Wilhite et al., 2007). Various economic sectors are adversely

affected, in particular agricultural production, energy generation, and water supply for domestic and industrial use. Habitat degradation, increased mortality of flora and fauna, and increased occurrence of wildfires are examples of the effects on the natural environment. Indirect impacts, such as increase on prices, unemployment or migration, arise as a consequence of the direct impacts, and may be felt in a much wider area, even reaching the global scale (Wilhite and Vanyarkho, 2000).

5   The occurrence and severity of drought impacts depends on the intensity and duration of the event, but also on the vulnerability of the society and the environment (Wilhite, 2000). As a consequence the conditions that produce negative socio-economic impacts are not necessarily the same for the different sectors that may be affected (Redmond, 2002). The timing of the event also influences the severity of impacts. Soil moisture deficit during the flowering stage of a crop or reduced domestic water supplies during the tourist season are examples of situations in which the socio-economic impact is aggravated due to the
10   timing of the drought.

The implementation of drought management plans by governing agencies can contribute to reducing the negative effects of drought by guiding decision makers in taking appropriate mitigation actions. However, the effectiveness and cost-efficiency of these actions rely on the selection of suitable indicators to monitor drought conditions, and to detect events at an early stage, gaining valuable time for mitigation measures to be implemented effectively and impacts to be mitigated. Examples of
15   actions that can be taken include retention of water; reallocation of available water resources; curtailment of current allocations; recommendations to plant less water-demanding or drought resistant crops; or prohibition of certain water uses (e.g. watering gardens or washing cars).

Indicator systems consist of drought indices with associated thresholds that allow classifying the event in categories of drought severity. A classical examples is the division of river flow into several categories. When the value of the indicator
20   crosses one of the thresholds, managers should decide whether to activate the corresponding responses defined in the drought management plan for that situation. Indicators and associated thresholds should be problem, context and user-specific (Kallis, 2008), and therefore an integrated management of droughts in basins where there are multiple users requires advanced drought detection systems based on multiple indicators.

Measurements from in situ networks and from remote sensing are complementary sources that can be used to build the
25   system of indicators for early detection and monitoring of drought conditions. In situ data is generally collected at specific points only. The advantage is the high temporal frequency of observations, and the availability of longer term records. Remote sensing techniques, on the other hand, offer cost effective and spatially continuous information over extended regions. Satellites allow drought events to be categorised over a certain area, rather than at point locations (Kogan, 2001; Famiglietti et al., 2015). Several satellite data sets are now available at a daily or at even shorter time scales, offering excellent potential to develop
30   sound drought monitoring systems in real time, and allowing to overcome the shortcomings of classical indicators based on in situ data sets that lack the spatial scale (e.g. Sheffield et al., 2014; van Dijk and Renzullo, 2011).

Keyantash and Dracup (2002) analyse a set of criteria to assess the usefulness of drought indicators for the assessment of drought severity and point out that while the robustness of an indicator provides insight into its consistent behaviour across differing conditions, assessing the accuracy of the information provided by the indicator requires a standard or benchmark for
35   comparison. This holds true for both remote sensing-based and ground-based indicators. A standard that offers an absolute

metric of drought is not easily available and likely does not exist, and as a result a common approach to evaluating the performance of remote sensing-based drought indicators is to assess their robustness by comparing them with other indicators such as flow, reservoir levels or widely used drought indices (e.g. Morid et al., 2006; Tsakiris et al., 2006; Vasiliades et al., 2011). Expert knowledge may also be used in practical applications as a benchmark to assess drought indicators such as in

5 Steinemann et al. (2015), who rely on regional water managers, drought decision-makers and other stakeholders' knowledge as a reference to develop, select and evaluate drought indicators. Expert judgement is also included, in combination with several indicators and model outputs, in the U.S. drought monitor (Svoboda et al., 2002) to develop a weekly map of drought conditions in the U.S. which itself is also frequently selected as a reference data set in the evaluation of the performance of drought indicators in the country (e.g. Anderson et al., 2011, 2013; Brown et al., 2008).

10 Since mitigating impacts is the purpose of drought indicators included in drought management strategies, impact data is especially suitable as a benchmark in this case. Drought impacts, however, are difficult to evaluate and are rarely monitored (Wilhite, 2011; Lackstrom et al., 2013). Several studies have analysed the connections of drought indices to quantifiable effects on agriculture, hydrology or forests (see Vicente-Serrano et al., 2012, for a review), but very few have applied the impact data (mostly crop yields) as a benchmark to assess indicators for drought detection (e.g. Potop, 2011; Sepulcre et al., 2012).

15 Recognising the potential of this kind of data for drought management, two large scale initiatives have recently been launched: the US Drought Impact Reporter (DIR) (Wilhite et al., 2007) and the European Drought Impact report Inventory (EDII) (Stahl et al., 2016). These have the objective to collect text-based impact records systematically with the aim to increase their availability and accessibility. Recent studies have explored the links of the EDII records to drought indicators (Bachmair et al., 2015a, b; Blauhut et al., 2015), though these have focused on the national scale, and it is recognised that further development

20 is required to allow analysis at the subnational scale (Stahl et al., 2016).

Despite their important role in mitigation of drought impacts, the selection and use of indicators and thresholds for decision making often suffers from a lack of scientific justification: only a few studies have analysed the choice of drought indicators in relation to drought management in practice (Steinemann and Cavalcanti, 2006; Steinemann et al., 2015). Moreover, the thresholds that have been selected to declare droughts are only rarely connected to the specific impacts that need to be avoided

25 (Wilhite, 2000). The aim of the current paper is to identify earth observation data sets that can be used to detect early stages of drought at the basin scale, as well as to what extent these data sets can anticipate drought impacts, and be used to inform operational land and water management. The innovation is that quantitative and qualitative drought impact information are applied as a benchmark in evaluating the utility of indicators derived from six different remote sensing data sets at river basin scale. Two aspects are considered in the assessment of the indicators against the benchmark data: how well do these

30 indicators reflect reported drought impacts and to what degree can these indicators be used to anticipate drought conditions and consequent impacts.

2   Material and methods

2.1   The Ebro basin

The Ebro basin, with an extent of 85,600 km², is the largest catchment in Spain. It is located in the north-east, bounded by the Pyrenees and Cantabrian mountain ranges to the north, and the Iberian System to the south. It is a highly regulated basin with

5   51 reservoirs (> 1 Mm3) and a total storage capacity of more than 7,500 Mm3, which supply water to more than 900,000 has of irrigated agriculture and more than 450 hydroelectrical plants (CHE, n.d.).

Analysis of the impacts of a recent drought event (2005–2008) revealed that agriculture and food production are the main sectors affected by drought in the area, but impacts to hydropower production, water supply to villages, food industry, recreational activities and ecosystem functions were also identified (Perez y Perez and Barreiro-Hurlé, 2009; Hernández-Mora et al.,

10   2013).

The Confederación Hidrográfica del Ebro (CHE) is the organization responsible for the management, regulation and conservation of water in the Ebro basin. The basin is divided into 18 management units, each of which has a board constituted of representatives of the different water users as well as of the basin authority to coordinate the use of the hydraulic infrastructures and water resources in their area.

15   A drought management plan for the basin was developed in 2007 to guide drought management actions (CHE, 2007). The plan defines a set of indicators to detect situations of hydrological drought in the Ebro basin and evaluate their severity. The indicators are built using observations from a rich network of in situ automatic stations. In the areas in which the flow is regulated by dams, water stored in reservoirs is considered the most robust indicator, but other variables such as water flow, snow depths or head levels in aquifers may also be taken into account. For areas with a natural or an almost natural flow regime

20   without reservoirs, the three-month water flow measured at representative stations is selected as the main indicator. In one of the management units, where there is no regulation and no representative rivers, groundwater levels are used as indicator.

The north-east of the basin, where the larger irrigation districts of the Ebro basin are located, was selected to evaluate the set of drought indicators against the qualitative text reports (Figure 1). This area was also the most affected by the drought period 2005–2006 (Hernández-Mora et al., 2013). It is composed of four management units (management units 12 to 15).

25   Figure 1 shows the management units further subdivided according to the main drought indicators currently selected in each: three-month water flow in the northern sectors (zones 120, 130, 140 and 150) and reservoir levels in the southern sectors. To differentiate non irrigated agricultural areas, Corine Land Cover map 2006 (CLC06) classes 211 (non-irrigated arable land), 242 (complex cultivation patterns) and 231 (pastures) have been used. The land cover class irrigated agriculture corresponds to the irrigation polygons provided by MAGRAMA (1997 version). The main irrigation districts are marked with dotted patterns

30   and are identified by the name of the main canal that serves them. For the evaluation of quantitative crop yield data as a benchmark, only five of the districts within this area were selected: Hoya Huesca (H), Somontano (S), La Litera (L), Monegros (M), and Bajo Cinca (B), including irrigated and rainfed cropland.
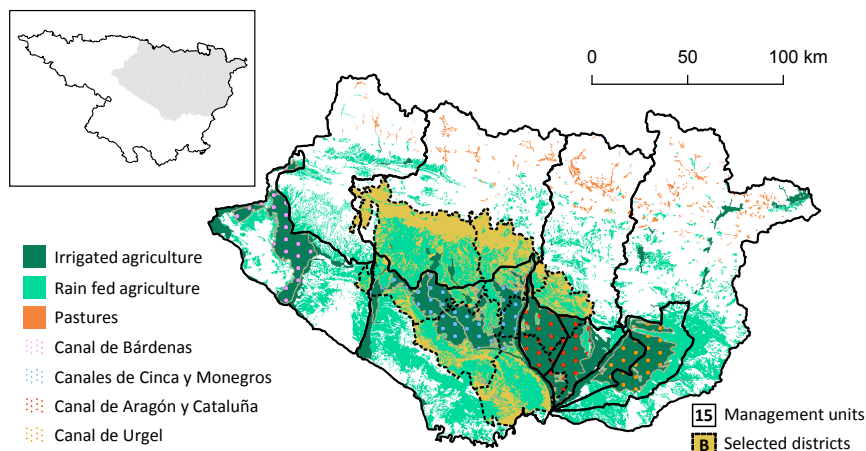
Figure 1. The north-eastern part of the Ebro basin with selected agricultural land cover information.

2.2 Input data sets

2.2.1 Remote sensing data

The analysis focuses on medium resolution global remote sensing products that are related to land surface hydrological and vegetation growth processes. Six commonly used remote sensing parameters were investigated: Precipitation (P), Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI), Gross Primary Production (GPP), top soil moisture (SM) and actual EvapoTranspiration (ET). In order to have one common time interval, monthly aggregated data sets were obtained for each parameter (Table 1). The remote sensing data has been aggregated per management unit. Pixels with at least 85% of their area within the management unit (30% in the case of soil moisture due to the coarse resolution) were considered in establishing the aggregate value for that unit. For the 1 km resolution LST, NDVI and ET remote sensing products, the results are also analysed by land cover type. This relates to pixels where at least 85% of the area consists of irrigated and rainfed agriculture land cover classes (see Figure 1). The selected remote sensing data sets are the following:

   Precipitation (P): The Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a gridded precipitation data set based on satellite and station data, designed with the main objective to support agricultural drought monitoring. It is a daily, quasi global product, with a resolution of 0.05°. The data set is available from 1981 to near-present. It is based on top cloud temperature measured by geostationary satellites and the Tropical Rainfall Measuring Mission (TRMM) satellite with a rainfall radar aboard. A detailed description of the product can be found in Funk et al. (2015). In this study, monthly aggregated rainfall values have been converted into Standard Precipitation Index (SPI) data sets. The SPI (McKee et al., 1993) is a normalised rainfall anomaly, computed by comparing the accumulated rainfall over a given period with the long-term record. The SPEI R-package developed by Beguería and Vicente-Serrano (2013) was used to calculate SPI for periods of 1, 3, 6, 9 and 12 months. The possibility to calculate the index for different periods is one of the strengths of SPI as it allows

to explore the effects of rainfall anomalies of different duration. SPI values calculated for shorter periods are associated to meteorological drought, while those calculated for longer period are often associated to hydrological drought (WMO, 2012).

Land Surface Temperature (LST): The MODIS (Moderate Resolution Imaging Spectroradiometer) product MOD11A2 offers day and night LST data sets, available at 1 km resolution as daily and 8-day products (http://modis.gsfc.nasa.gov/data/
5 dataprod/mod11.php). The daily daytime LST data have been used for the current study. LST is based on longwave emissions in the thermal infrared range (10 to 12 μm).

Vegetation health (Normalized Difference Vegetation Index, NDVI): The MODIS Vegetation Indices product (MOD13) provides information on the active leaf chlorophyll, and thus indirectly on the photosynthetically active process. NDVI describes the ratio of the difference and sum of reflected radiances in the red (0.65 μm) and near-infrared parts of the spectrum
10 (0.9 μm). MOD13 is available at different resolutions: 16-day (250 m, 500 m and 1 km) and monthly (1 km) (http://modis.gsfc.nasa.gov/data/dataprod/mod13.php). The monthly 1km data product has been used in the current analysis.

Gross Primary Production (GPP) and PsnNet: GPP describes the daily gross carbon flux as a result of the photosynthesic process and is thus suitable to detect the effects of drought on biomass production. The MODIS GPP product (MOD17) applies a light-use efficiency model based on MODIS FPAR (fraction of photosynthetically active radiation) data, meteorological
15 data and biome-specific parameters. It is available at a spatial resolution of 1 km as 8-day composites or as annual values (http://modis.gsfc.nasa.gov/data/dataprod/mod17.php). The product also includes Net Photosynthesis (PsnNet), which corresponds to the GPP minus the maintenance respiration for leaves and roots. Additional background information can be found in Running and Zhao (2015).

Soil Moisture (SM): The soil moisture product considered is taken from the Soil Moisture CCI project, part of the ESA
20 Programme on Global Monitoring of Essential Climate Variables (ECV) (Liu et al., 2011, 2012; Wagner et al., 2012). Three daily products are available (data sets based on active, passive or merged microwave instruments) for the period 1978 to 2014 at a spatial resolution of 0.25 degrees (http://www.esa-soilmoisture-cci.org/). Higher spatial resolution products are only available for certain areas. The product used in the current analysis is the merged CCI SM data set. The data is based on C-band scatterometers and multifrequency radiometers.

25 **EvapoTranspiration (ET):** There are currently three global data sets of actual ET in the public domain. These are the MODIS ET product (MOD16, https://modis.gsfc.nasa.gov/data/dataprod/mod16.php) developed by the University of Montana (Mu et al., 2007, 2011) and supported by NASA; the Surface Energy Balance System SEBS developed by Su (2002), and the Global Land Evaporation Amsterdam Model (GLEAM) developed by Miralles et al. (2011) which is available through www.gleam.eu. In addition, there are global ET products that are quasi open-access, including the Atmosphere–Land Exchange
30 Inverse Model (ALEXI) being developed by Anderson et al. (1997) from the USDA in conjunction with Hain et al. (2009) from NOAA; the Operational SEBS (SEBSop) of the USGS (Senay et al., 2013; Chen et al., 2016) and the C.M.R.S. Evapotranspiration (CMRSET) published by Guerschman et al. (2009) from CSIRO in Australia. In this paper an ensemble product based on these individual products with accumulated monthly ET values at a pixel resolution of 250 m x 250 m is used. This ensemble ET product (ETens v1.0) is available from the Water Accounting Group of UNESCO-IHE (www.wateraccounting.org). The
35 six individual ET models considered all use different parts of the spectrum, which reinforces the power of this tool.

Table 1. Selected remote sensing products

Parameter	Product	Pixel size	Original time interval
P	CHIRPS	0.05 deg	Daily
LST (day)	MOD11A2	1 km	Daily
NDVI	MOD13A3	1 km	Monthly
GPP and PsnNet	MOD17 (NTSG)	1 km	Monthly
SM	Merged SM product	0.25 deg	Daily
	(CCI project)		
ET	Ensemble	250 m	Monthly

2.2.2 In situ data

In situ data of reservoir levels and inflow and river flow from the basin measurement network were used to calculate the Status Index (I_e), a normalised monthly index used by CHE to homogenise the different indicators (CHJ, 2007):

$$\text{If} \quad V_i \geqslant V_{avg} \quad \rightarrow \quad I_e = \frac{1}{2}\left[1 + \frac{V_i - V_{avg}}{V_{max} - V_{min}}\right] \tag{1}$$

$$\text{5} \quad \text{If} \quad V_i < V_{avg} \quad \rightarrow \quad I_e = \frac{V_i - V_{min}}{2(V_{avg} - V_{min})} \tag{2}$$

where V_i is the value of the indicator for month i and V_{avg}, V_{max} and V_{min} are respectively the average, maximum and minimum values of the indicator derived from historical data. Based on this Status Index (which is a value between 0 and 1), the situation under analysis is classified by the authority as normal ($I_e > 0.5$), pre-alert ($0.5 > I_e > 0.3$), alert ($0.3 > I_e > 0.15$) or emergency ($I_e < 0.15$).

10 The indicators selected by CHE for each of the management areas were used for the analysis presented here. These are the values of reservoir volume for the regulated areas (122, 123, 131, 132, 141, 151), inflow into the corresponding reservoir(s) for the upstream areas (120, 140, 150), and runoff at a selected station for management area 130.

2.2.3 Benchmarking data sets

Two different tests were carried out using drought impact data sets as benchmark to assess the ability of remote sensing based 15 indicators to provide early drought detection information during the period 2000–2012. In the first test, text-based records of drought occurrence and impacts collected from a review of local news were used as benchmark for the comparison (i.e. qualitative information). In the second test, the use of crop yield statistics as a benchmark of drought impact on agriculture is explored (i.e. quantitative information).

Text-based records were collected from a review of regional news. "El periódico de Aragón", the second largest newspaper in 20 average daily circulation in the Aragón region, with an online record going back to September 2001, was selected for the review.

All news items containing the word "drought" were reviewed and relevant records of drought events and impacts referring to the area of study were tabulated. For each entry the location, period, description, and, in case of reported impacts, the affected sector were noted. The affected sectors were labelled as *rainfed cereals*, *irrigated agriculture*, *livestock*, *water quality*, *fire*, *water supply*, *energy* and *others*. A distinction in the analysis is made between the mention of drought, the acknowledgement
5 of drought by the authorities, the reported mitigation measures, and news items retrospectively reporting on droughts.

The limit between indicators and impacts is not always clear. For example, low flow or reservoir levels are considered an impact of meteorological drought in some analyses, while these serve as indicators of hydrological drought in others. Here we limit the definition of drought impacts as the effects of drought on people, economy and/or the environment.

Crop yield data of winter cereals both for irrigated and rainfed cropping systems was obtained for the five selected districts
10 in Huesca (H, S, L, M and B). Only winter cereal crops with larger cultivated areas were selected: two and six-row barley (irrigated and rainfed), wheat (irrigated and rainfed), and rice (irrigated). The two and six-row barley types refer to the number of fertile spikelets in the spike.

2.3 Correlation between remote sensing data and the benchmarking data sets

The correlation of the remote sensing time series with the timelines of drought occurrence and impacts was analysed in terms
15 of strength of the relationship and anticipation. The strength of the relationship is related to the predictability of the occurrence of drought and drought impacts provided by the remote sensing time series.

Anticipation reflects the ability of the remote sensing data sets in providing early information and gaining time to undertake actions. These two characteristics of the relationship were examined using a lagged correlation analysis, i.e. establishing the correlation where the remote sensing data set is shifted in time with respect to the benchmarking data set. In this way the
20 impact occurrence was compared to the variables represented by the remote sensing time series in the 24 preceding and following months.

The sample cross correlation function (CCF) as implemented in R (R Core Team, 2016) was used for the analysis. The cross-correlation function ($\rho_{x,y}$) can be expressed as (Chatfield, 2004):

$$\gamma_{x,y}(\tau) = cov(X_t, Y_{t+\tau}) \tag{3}$$

25 $$\rho_{x,y}(\tau) = \frac{\gamma_{x,y}(\tau)}{\sigma_x \sigma_y} \tag{4}$$

For $\tau = \pm 1, \pm 2, \ldots$, where τ is the lag and σ_x and σ_y are the standard deviations of the time series x_t and y_t. The set of $\gamma_{x,y}$ coefficients corresponds to the cross-covariance function.

The reference drought periods used for the correlation provide a binary record; indicating the occurrence or non-occurrence of drought events in each month, without quantifying their intensity. To obtain an insight into the severity of the events, the
30 use of annual crop yield data was explored. The correlation of each annual crop yield value to the monthly values of the remote sensing time series from the start of the hydrological year in September to the end of the following calendar year was analysed. This was done to detect the key months in which the occurrence of drought conditions lead to impacts on the
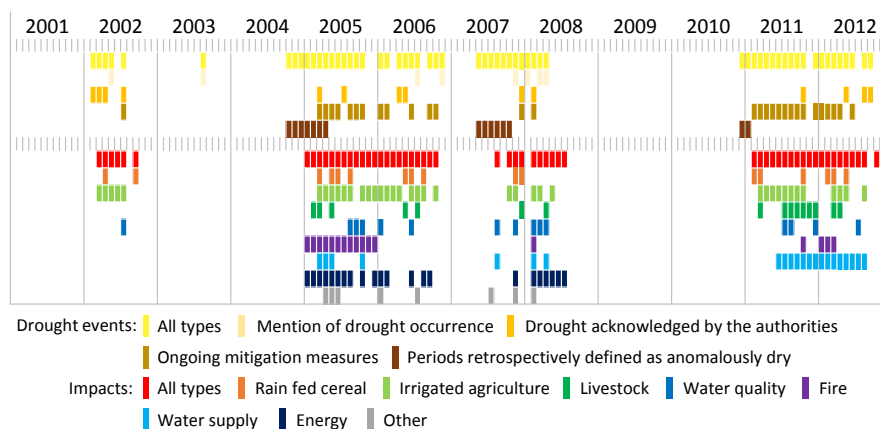
Figure 2. Timeline of drought events (upper part) and impacts (lower part) for the north-eastern Ebro basin during the period 2001 to 2012 based on a comprehensive local newspaper review.

(annual) crop yield. The comparison was performed for three rainfed areas and three irrigated areas. These were selected to correspond with the management units so that a relation could be established with the areas of influence of the reservoirs (Figure 1). The areas selected included the rainfed agriculture areas of Hoya Huesca (HH0, corresponding to management unit 140), Monegros-Bajo Cinca (MB0, corresponding to management unit 141), and in the five districts together (AA0) and the

5 irrigated agriculture in Hoya Huesca-Monegros (HM1, corresponding to management unit 141), La Litera-Bajo Cinca (LB1, corresponding to management unit 131), and in the five districts together (AA1).

3 Results

3.1 Drought events and impacts

The timelines of drought events and impacts derived from the review of local news are illustrated in Figure 2. Three drought

10 events can be distinguished in the Ebro basin: a short drought event at the beginning of 2002, a multi-year drought from the end of 2004 to the spring of 2008 and a shorter duration drought during 2011 and 2012.

The first colored row (yellow) in the figure represents the months in which drought was taking place according to the records found in the newspapers. Four types of record can be distinguished for this first row, represented by the following four rows: (1) general mention of drought conditions, (2) mention of the acknowledgment of drought by authorities (national, local

15 government or water authority), (3) mention of ongoing drought mitigation measures, and (4) mention of earlier periods of rainfall deficit in the newspaper but described in retrospect. This last type corresponds mainly to news about the publication or communication of analysis performed by the scientific community or the water mangers describing an ongoing or past drought. The first line of the second block (red) reflects the occurrence of drought impacts described in the newspaper, while in the following rows these impacts are disaggregated by the affected sector.

Based on the records gathered from the newspaper records, the following descriptions of the hydrological years affected by drought episodes were constructed:

In 2002, after a dry winter the availability of water in the reservoirs was low. A first reference to drought in the press appeared in February 2002. At the start of the spring, which is the beginning of the irrigation season, water curtailments were reported for Bardenas irrigation system. In the beginning of April, Agricultural Associations reported losses of 20% of rainfed cereal crops in Aragon and at the end of the month the impact of drought in the area was acknowledged by the Ministry as well as by the local government. In July, the flow of the Ebro in Zaragoza was half of the minimum 30 m^3/s that has been set to warrant water quality. In September a reduction of 40–70% in olive oil production in the areas of Bajo Cinca, Medio Cinca and La Litera was reported in the news. General mention of impacts on pastures, hydroelectricity production and employment in the primary sector during that drought period appeared in retrospect, but these reports did not go into detail.

The hydrological year 2004–2005 was depicted as the driest on record. The combination of cold and dry conditions during the first part of 2005 produced significant losses in the agriculture and livestock sectors. First impacts were reported in February 2005 (lack of pastures production after five months without rain). From then, and until September 2006, the newspaper reflected a succession of impacts in different sectors, including all crop types, pastures, forests, livestock production, water supply to the population, wildlife, economy, recreational activities, hydroelectricity, water quality, employment and politics. The drought was already acknowledged by the authorities since March 2005, and the first mitigation measures were announced shortly after. This was that the regional government increased to 50% the area of land, rainfed or irrigated, that could be set aside to remain fallow. In June, aid measures were approved by royal decree.

Reservoir levels increased during the first half of the hydrological year 2005–2006, but the system failed to recover completely from drought before levels started decreasing again in April 2006, and at the beginning of the summer levels were lower than the previous year. After a hot summer, storage started to recover again and in December 2006 the government considered the drought as having ended. Intense rains starting in February 2007 were followed by a period of precipitation deficit from May to February 2008. A few problems of water supply to certain villages were reported in August 2007 and flows were below the minimum required to warrant water quality in October. Impacts on agriculture and hydroelectricity started to be reported again in October. Abundant rains during spring 2008 constituted a first step towards the end of the drought episode.

The hydrological year 2010–2011 was characterised by lower than average precipitation and high temperatures. In February 2011 the newspaper showed the first reference to an emerging drought and its impact on the sprouting of winter cereal. This drought especially affected the Bardenas irrigation district. The Riegos del Alto Aragón and Canal de Aragón y Cataluña districts were also affected. All the systems managed to reach the end of the irrigation season, but with restrictions of more than 60% on water quotas. Grapes and olives were the most damaged crops, but in general the food production in the area was defined as satisfactory at the end of the season. The following hydrological year (2011–2012) started with low reserves and a dry winter and spring, with the exception of November, which was a particularly wet month. In particular, the middle sector of Huesca revealed drought affected areas. Extensive livestock farming, fodder and cereal production were the most impacted sectors. The risk of fire was reported to be high, even during the winter, which translated in a higher number of fires.

3.2   Correlation of text-based records and remote sensing indicators

The information on drought occurrence and impacts obtained in the previous step was used as a benchmark data set to assess the ability of the remote sensing based data sets to provide early detection. Figures 3 and 4 present the results of the cross correlation of the remote sensing data sets to the timelines of drought events (i.e. upper records in Figure 2) and impacts (i.e.

5   all other records in Figure 2) respectively. The x-axis expresses the time lag in months between the remote sensing data sets and the timeline of drought events and impacts (τ in equations 3 and 4). The central line ($x = 0$) corresponds to the correlation of the two data sets in the same month. Negative values of x refer to correlations between impact time series at time t and remote sensing values at each of the 24 months before t ($\tau = 1, \tau = 2, \ldots, \tau = 24$). Strong correlations on this side of the central line reflect the ability of the data set to anticipate the occurrence of drought events and impacts.

10   Figures 3 and 4 have similar correlation patterns, with the second showing higher anticipation. This result was expected because Figure 3 is based on records reflecting climatic and hydrologic anomalies and deficits, and these processes precede the impacts.

SPI shows the strongest correlations for both events and impacts. For SPI values calculated for longer aggregation periods the correlation grows stronger, while the anticipation is slightly reduced. The best correlation-anticipation relationship is obtained

15   for SPI-6 and for SPI-9. For these indicators, the correlation is also stronger in the southern areas. This is probably because most of the socio-economic activities are concentrated in these managed areas, and therefore the impacts and media attention are likely to be higher. The results show that SPI-6 and SPI-9 are most suitable for predicting impacts, together with NDVI and ET; achieving an anticipation of 6 months with a sufficient correlation ($r^2 > 0.6$). This provides useful information for activating drought mitigation measures.

20   Soil moisture also shows good anticipation, albeit with weaker correlations. This may be due to the coarser spatial resolution of the data set. Higher resolution soil moisture products (e.g. Scott et al., 2003; Alexandridis et al., 2016) could be considered for future studies. NDVI and ET data sets show a strong negative correlation with drought occurrence and impacts, which would be expected from a biophysical perspective. NDVI shows better anticipation, preceding the impacts in most of the units by more than 6 months. ET shows a slightly stronger correlation in the rainfed areas, while no distinction is seen between

25   rainfed and irrigated areas for LST and NDVI. LST has a positive correlation because evaporative cooling is diminished during drought events which prompts the land surface temperature to rise. LST correlation to events is stronger than to impacts, but the degree of anticipation is lower for the former.

In situ indicators based on water levels and flows show varied level of anticipation for the different areas. Most of them provide early information on drought occurrence and impacts from 6 to 9 months in advance, but there are two areas where the

30   indicator offers no anticipation (management area 140) or even no correlation with the benchmark data sets (management area 123). The reason for these exceptions is unclear.

Indices derived from both GPP and PsnNet present weak or no correlation for most of the areas, with only some of the rainfed areas showing moderate positive correlations. The reason for this may lie in the formulation of the MOD17 product.
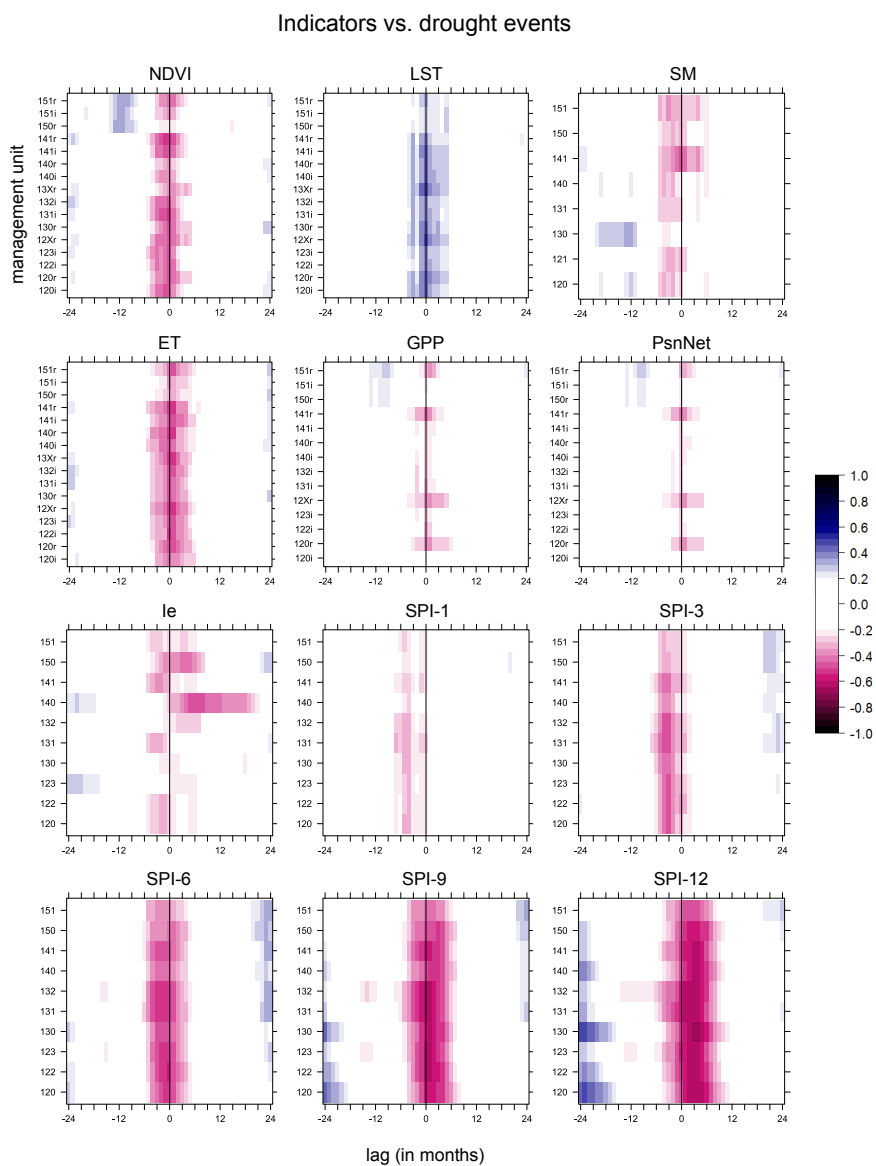
Figure 3. Cross correlation of drought indicators and drought events at multiple time lags. The numbers in the y-axis represent the management areas depicted in Figure 1. For NDVI and LST, irrigated (i) and rainfed (r) crops within the areas are distinguished. The x-axis represents the shift in months between the two data sets. The indicator built from in situ data (I_e) is also included.

Indeed, limitations of the product in capturing spatial and temporal variability in croplands have been reported (Zhang et al., 2012; Verma et al., 2014).
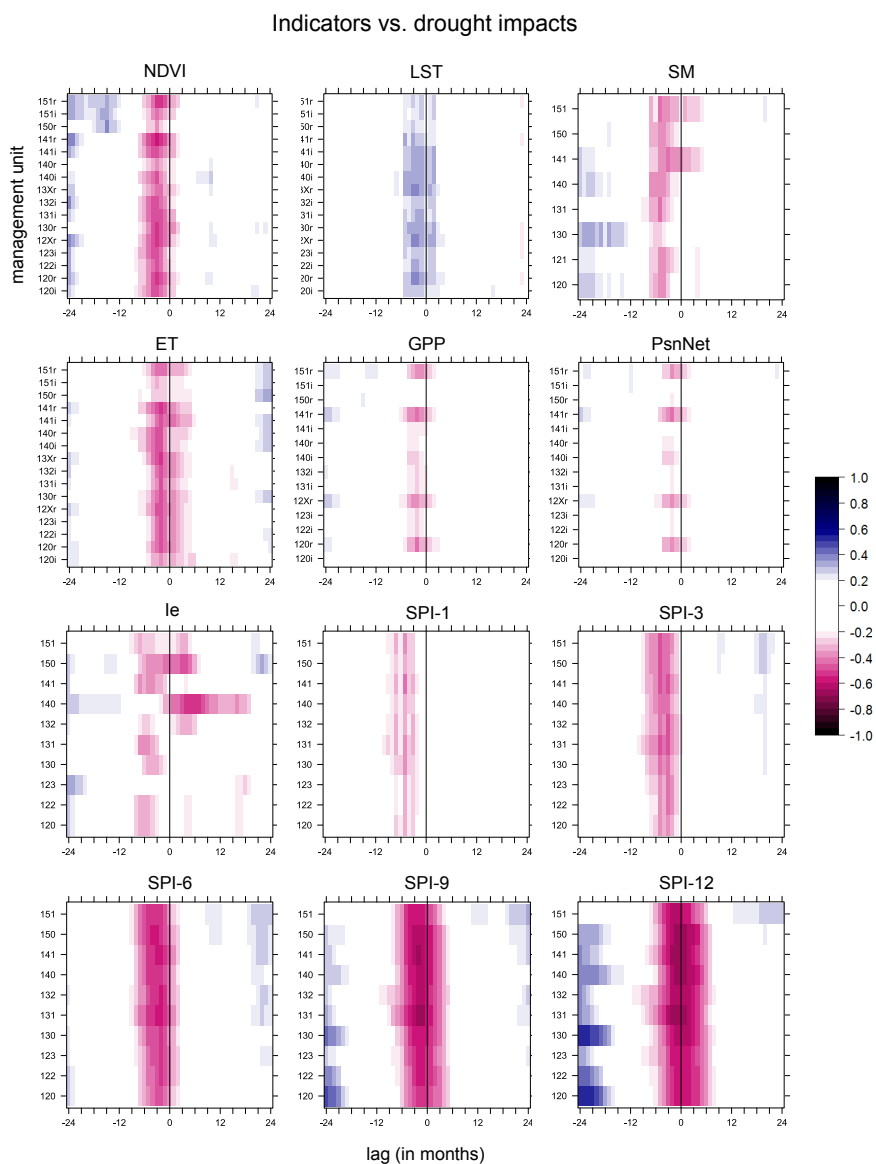
Figure 4. Cross correlation of remote sensing data sets against the timeline of reported drought impacts (all types).

3.3   3.3 Correlation of crop yield and remote sensing indicators

The results of the correlation analysis between the remote sensing data time series and the annual crop yield for the main irrigated and rainfed cereal crop types in the selected districts in Huesca are represented in Figure 5 and Figure 6. Every parameter is tested for the six areas. The crop types are represented on the y-axis and the months on the x-axis. The latter spans
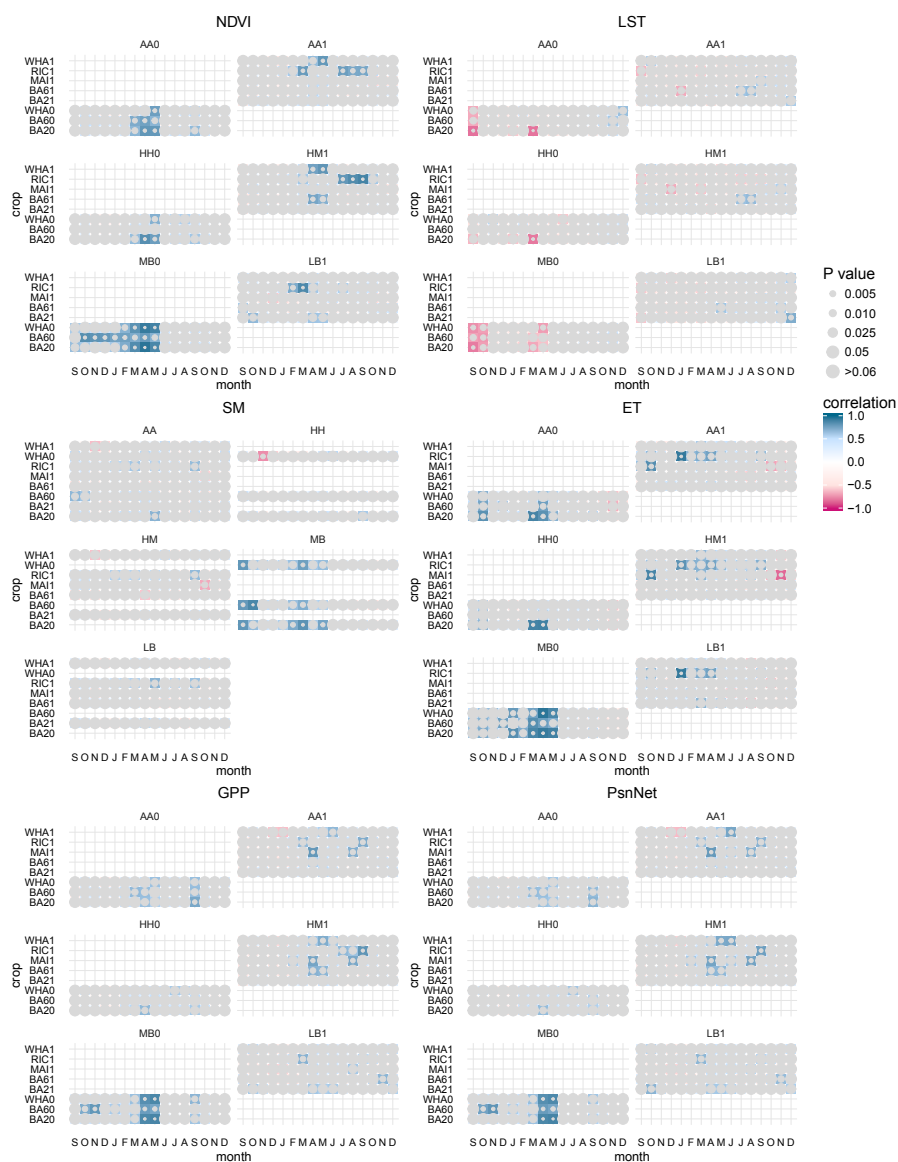
Figure 5. Correlation between remote sensing drought indicators and crop yield data. Rainfed areas and crops are marked with 0 and irrigated areas and crops with 1. The crops are irrigated and rainfed wheat (WHA1 and WHA0), irrigated rice (RIC1), irrigated maize (MAI), irrigated and rainfed six-row barley (BA61 and BA60), and irrigated and rainfed two-row barley (BA21 and BA20). The colour gradient reflects the sign and strength of the correlation, while the size of the inner grey circle corresponds to the significance of the correlation.

from the start of the agricultural year in September to the end of the following calendar year. The colour gradient reflects the sign and strength of the correlation, while the size of the inner grey circle corresponds to the significance of the correlation.
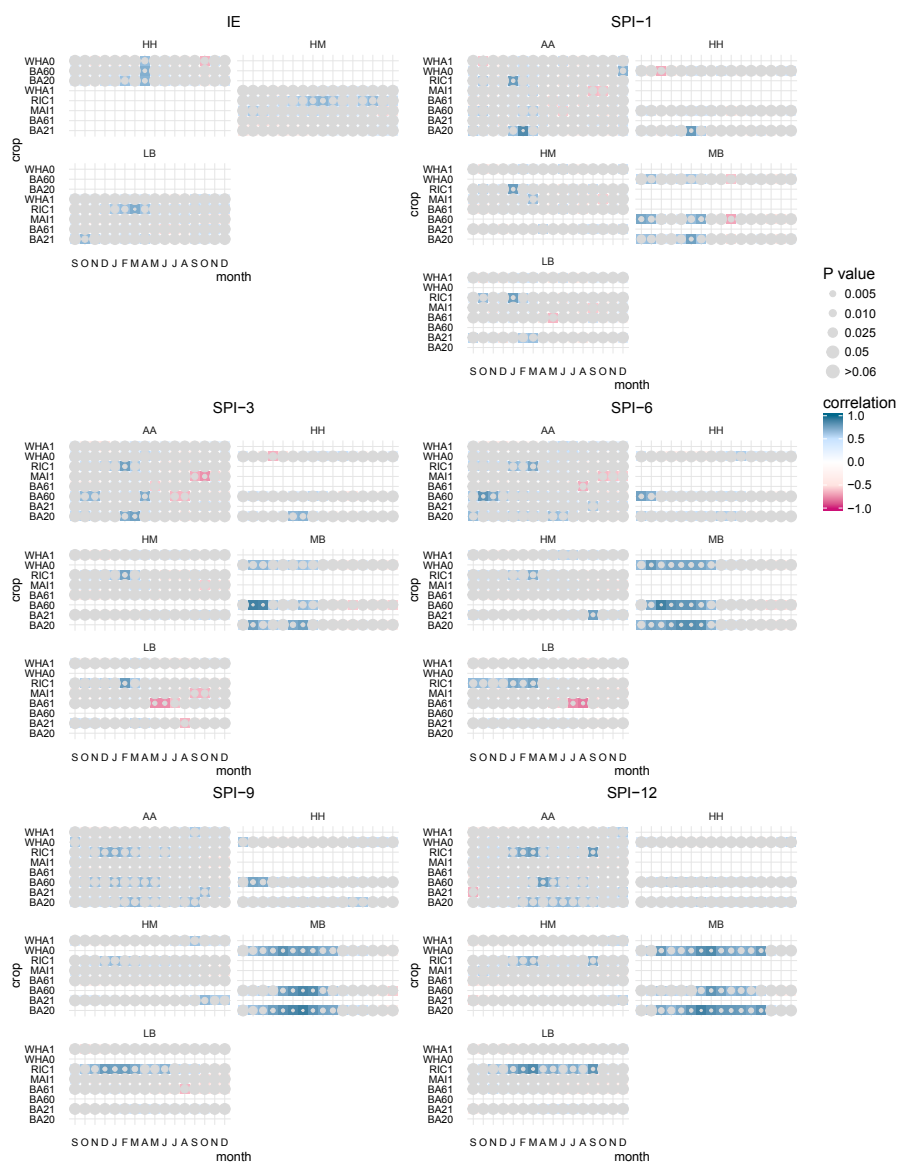
Figure 6. Correlation between drought indices (SPI and Reservoir index) and crop yield. Rainfed areas and crops are marked with 0 and irrigated areas and crops with 1. The crops types are irrigated and rainfed wheat (WHA1 and WHA0), irrigated rice (RIC1), irrigated maize (MAI), irrigated and rainfed six-row barley (BA61 and BA60), and irrigated and rainfed two-row barley (BA21 and BA20). The colour gradient reflects the sign and strength of the correlation, while the size of the inner grey circle corresponds to the significance of the correlation.

NDVI and ET present some of the strongest positive correlations, especially between the remote sensing measurement during the spring (MAM) and the yield of rainfed crops. This is in agreement with the results obtained by Vicente-Serrano et al. (2006)

who observed a higher correlation between barley crop yield and NDVI for the month of March at a location in the Ebro River valley. LST shows also strong correlations with rainfed crops in March and at the beginning of the season in September (S). The pattern is less clear for irrigated crops, probably because their water supply is less dependent of the rainfall. The strongest correlations in this case appear for rice crops with ET and NDVI, mainly at the start of the year.

5   Despite irrigated crops directly depending on reservoir supply, only rice shows significant positive correlations with the index based on reservoir levels for the two irrigated areas tested (HM, corresponding to management area 141 and LB corresponding to management area 131). The reason can be that rice is especially drought sensitive, since it has shallow roots and therefore a low depth of readily available soil water, which is the fraction of total available soil water that crops can obtain from the root zone without experiencing water stress. This fraction is 0.2 for rice (Allen et al., 1998). The rest of the tested crops have

10   a higher value of this fraction and they experience stress when more moisture is depleted. The rainfed crops in the HH area (corresponding to management area 140) show correlation with the Status Index based on reservoir inflow, in April.

      Soil moisture, GPP and PsnNet do not show a clear pattern against reported crop yield, except for a strong positive correlation in one of the areas (MB). These correlations appear in the spring (especially for GPP and PsnNet) and at the beginning of the hydrological year.

15   SPI has positive correlations at the start of the season, which are particularly strong in the MB area. In some cases also a negative correlation during the summer emerges, especially for shorter term SPIs. It can also be observed that the stronger correlations appear later with longer term SPIs.

      Rainfed two-row barley (BA20) in March stands out as the crop with the stronger overall correlation with the different indicators. BA20 is one of the major crops in the area, with a maximum cultivated surface for the period 2000–2012 of 170,914

20   ha of the total of 204,614 dedicated to herbaceous crops (in 2008), and a minimum cultivated surface of 130,764 ha (2012). Maize is the second commonest crop with an average crop surface of 41,292 ha during the period. Figure 7 illustrates the correlation of two-row barley to each of the indicators for the rainfed crops in the Monegros-Bajo Cinca area (MB0), which has been selected as an example. This shows the crop yield for the different years against the value of each resepective indicator.

      Three years stand out in Figure 7 for having extreme low indicator values (high in the case of LST) for all variables: 2005,

25   2008 and 2012. Values are also low for year 2000 for the data sets for which it is available. These three years correspond with hydrological years of reported impact in the area identified in the previous section.

      The lowest crop yields were obtained in 2012 (1342.5 kg/ha). This is in agreement with the information in newspapers reporting that drought that year especially affected cereal production in the middle sector of Huesca, the area of focus of this test. Accordingly the remote sensing parameters present some of the lowest (highest in the case of LST) values for the period.

30   Only SPI-6 presents a value that is well above the minimum. This is caused by November 2011 being a particularly wet month in the middle of the drought period, thus moderating the value of SPI-6. For longer term SPI values this positive anomaly is compensated by the negative anomalies of the rest of the months.

      Crop yields were very similar in 2005 and 2008 (1662.3 and 1800.1 kg/ha respectively) and so is the behaviour of most of the variables. The main differences appear in LST, with the 2005 LST for March being more than 2 degrees higher than in 2008

35   (23.8 and 21.3 degrees respectively), and SPI-3, which is less extreme in 2008 (–0.68 compared to –1.51 in 2005). The reason
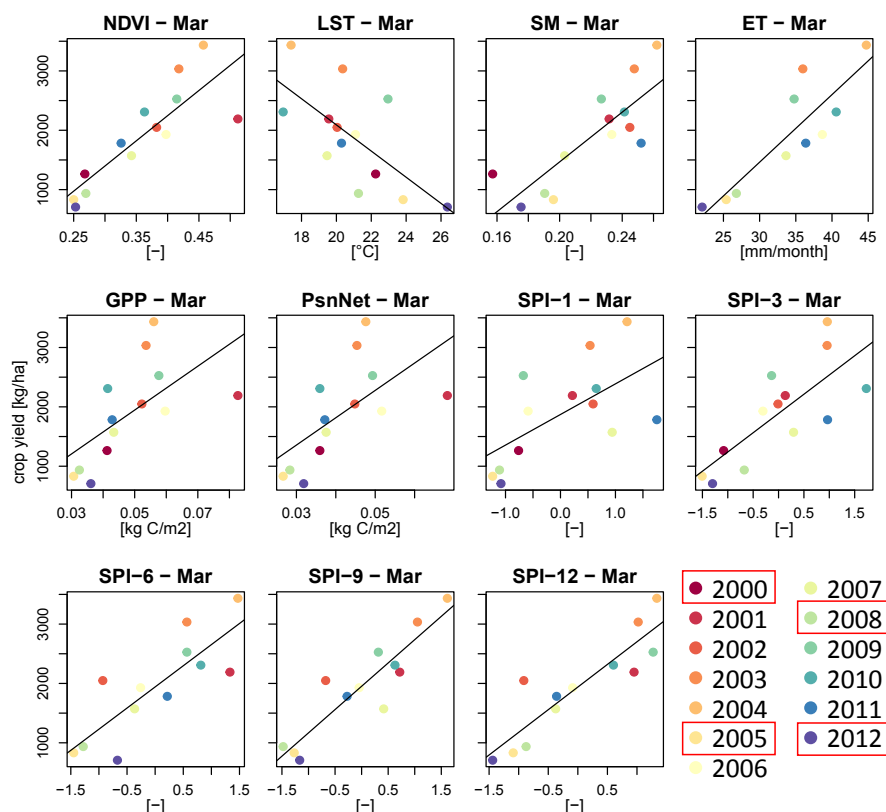
Figure 7. Correlation of the remote sensing drought indicators for the month of March to annual rainfed two-row barley yield in Monegros-Bajo Cinca districts (MB). For LST, NDVI, SM, ET, GPP and PsnNet monthly means were used.

for this difference is the earlier start of spring rains in 2008. Both hydrological years start with an exceptionally dry period that extends to April in 2005 and to March in 2008 after which the spring rains improve the situation.

There is a second group in the middle sector of the plots that includes the rest of the years for which drought impacts on rainfed agriculture were reported in the analysed media, 2011 (3551 kg/ha), 2006 (3857 kg/ha) and 2002 (4249 kg/ha), together

5 with the hydrological year 2006–2007 (3115 kg/ha), for which no impact was reported in the regional press. Local press for the area of Alto Aragón, however, reported a lack of rain from October to March, aggravated with high temperatures, in Monegros and Bajo Cinca that had an impact on rainfed cereals and pastures.

March values of SPI-3 for these years are close to the mean and only 2002 presents strong negative anomalies for SPI-6. In 2006 and 2007 the precipitation deficits start in April and May respectively and for 2006 the impacts are reported only after

10 that month. Hydrological year 2001-2002 shows dryer autumn-winter conditions according to SPI-6.

The results of this second tests present a consistent behaviour of the indicators with respect to the different levels of crop yield among the analysed years in rainfed areas. As in the previous test, NDVI, ET and SPI stand out for having stronger correlations. Most indicators present very similar March values for the years of severe drought, clearly differentiated from the

behaviour of years of moderate drought and years of no drought. The only exception is LST, in which a year where drought was not reported and yields were normal, such as 2009, has similar LST values in March than the years of severe drought. This indicates that LST may not be a good indicator of drought on its own, but can still be useful in combination with other indicators.

4 Discussion

4.1 Use of impact records as drought reference

The review of text-based records allowed a detailed reconstruction of the drought events during the period studied. The cross-correlation of the timelines of drought events derived from this review to the set of indices derived from remote sensing data sets revealed the potential of the latter to provide early detection of drought events. However, this binary information has the limitation that it does not allow to objectively quantify the severity of the events. For example, in the case of rainfed agriculture, the information on impacts collected from the newspaper does not allow for differentiation between those years in which production was extremely low as a consequence of drought conditions and those years in which production was only partially affected by drought. Other studies have also suggested a link between impact severity and the number of records reporting them (e.g. Hernández Varela et al., 2003; Bachmair et al., 2015a), but this needs to be taken carefully since the media coverage of a drought event is also highly influenced by the socio-political context in the affected area (Sonnett et al., 2006; Llasat et al., 2009).

A few additional aspects concerning reliability were noticed while processing the records from the press: (i) Accuracy: The information on drought occurrence reported in the newspaper may not be accurate. For example impacts due to other causes may be attributed to drought, or other phenomena such as normal summer shortages may be described as drought. (ii) Completeness: Reporting of drought occurrence in the newspaper is not systematic and therefore some impacts may be missing. Records referring to specific types of impacts are more likely to have gaps. However, when all types are aggregated, part of the gaps in each of the disaggregated data sets will likely be filled with records from the other data sets. (iii) Bias: Public or political interest or concern about drought (or even scarcity of other relevant news) can motivate overstatement of drought impacts. (iv) Scale: drought events affecting only a small area within the region covered by the newspaper may not be reported.

Crop yield data, on the other hand, allowed for a more objective identification of the drought events that had higher impact on agriculture, though the yield data does have the disadvantage that may only be reported on an annual basis. The examination of the behaviour of the remote sensing parameters in the years with similar yield data provided an insight on the reliability of the parameter as an index. Similar values of the parameter for years of similar final crop yield indicate the robustness of the indicator. For the period of analysis, the occurrence of drought in the years in which low yields were obtained is confirmed by the media records, but despite that the water availability is a determinant factor for rainfed winter cereal yield, other factors such as frost, floods, plagues and diseases could have further reduced the annual yield. However, for March values, there are no anomalies that suggest these factors had a strong influence in the low annual yield values.

Crop yield data can also be a useful reference to identify thresholds of drought severity classes. These thresholds could be derived based on the differences observed between the groups of years with severe, moderate and no drought conditions, although a longer data series than was used in this study is recommended to provide a more robust estimate of threshold values.

There are several factors that play a role in the severity of the impacts due to drought conditions, including coping capacities and water management (e.g. drought may not lead to impacts in irrigated areas). Variations in these factors can alter the relationship between the indicators and the impact. It should also be noted when using drought impacts as a benchmark of drought occurrence, that the absence of certain types of impacts as a result of sound drought management does not imply that there is no drought (Smakhtin and Schipper, 2008), though even with perfect management there will always be some kind of impact. For example, a reduction of income as a consequence of substituting the usual crops by less productive alternatives with lower water requirements constitutes a clear impact, even if the yield in kg/ha is not affected. The influence of management is probably also the reason for irrigated land showing less clear correlation patterns than drought in rainfed areas in both analyses. A wider view that considers as many different types of impacts and affected sectors as possible can help overcome the effect of management when using this type of data as a benchmark of drought occurrence. Initiatives such as the US Drought Impact Reporter and The European Drought Impact report Inventory can play a useful role in providing that broader view.

4.2 Early drought detection with remote sensing products

Early information on emerging droughts benefits mitigation strategies by increasing the time available for managers and affected communities to take action. The requirements for drought early warning range from a few weeks to several months (UNISDR, 2009). The results show the potential of the tested products to anticipate up to some 6 months reported drought impacts at basin scale. SPI, NDVI and ET products stood out in both analyses as particularly suitable datasets to detect early stages of drought at the basin scale and anticipate drought impacts.

The trade-off between the anticipation of the information and its reliability is also illustrated by the results. The lower reliability associated with earlier information detection of conditions that may lead to drought implies that often the situation may not evolve into a drought event. However, that information is still highly valuable as it allows the stakeholders to get ready to undertake mitigation actions if necessary.

The remote sensing products tested can enhance early warning capacity and therefore contribute to the shift from reactive to proactive management recommended by the European Commission (Commission of the European Communities, 2007) and the United Nations (UNISDR, 2009) and being undertaken by many institutions (Iglesias et al., 2009). As remote sensing data products generally have a global coverage, this contribution would therefore be especially useful in areas with less in-situ data available.

Remote sensing products also have the potential to provide information at a finer spatial detail than the management units and land cover classes considered in this study, allowing the detection of local drought events that may remain unnoticed when the pixels are aggregated to the scale of the land cover classes considered.

5 Conclusions

The aim of this research was to test the ability of remotely sensed datasets to detect early stages of drought at the river basin scale, with particular attention to their capacity to anticipate drought impacts and gain time to inform operational land and water management. Media records from regional newspaper proved to be a helpful source of information that allowed a detailed reconstruction of drought events and impacts. The analysis using this data as a benchmark revealed the potential of the tested medium resolution remote sensing products to anticipate reported drought impacts on irrigated and rainfed areas at basin scale up to some 6 months. The best correlation-anticipation relationships were obtained for SPI, NDVI and ET. SM and LST also showed potential to anticipate drought, but with weaker correlations. GPP and PsnNet from MOD17 presented weak or no correlation for most of the areas, with only some of the rainfed areas having moderate positive correlations. The index based on in-situ data currently used in the basin also provides early detection, and with the exception of two of the management units, the anticipation of drought impacts is better than that provided by the remote sensing indicators. However, the correlation of the indices based on SPI, NDVI and ET to anticipate drought impacts was found to be stronger. The use of quantitative impact data of crop yields as benchmark showed a consistent behaviour of the remote sensing indicators with respect to the different levels of crop yield in rainfed areas among the analysed years. SPI, NDVI and ET stand out for having stronger correlations, reinforcing the findings of the first analysis. In both analyses drought on irrigated land showed less clear correlation patterns than drought in rainfed areas.

Altogether, the results confirm remote sensing products' ability to anticipate reported drought impacts and therefore provide a useful source of information to support drought management decisions at the basin scale. However, further analysis of manager's information requirements and response options is required to better assess the usefulness of these type of products in informing specific operational drought management decisions.

6 Data availability

The remote sensing data used in this research is openly available. The sources are mentioned in section 2.2.1. In situ data from the basin measurement network can be downloaded from the Ebro basin authority site (www.chebro.es). Crop yield data can be downloaded from the site of Aragon government (www.aragon.es). The data set derived from the review of newspaper records is made available as supplementary material. The corresponding news articles can be accessed online at www.elperiodicodearagon.com.

Competing interests. The authors declare that they have no conflict of interest.

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