Combined Drought Indicator (CDI) v3

The Combined Drought Indicator (CDI) is used to detect and monitor areas that either are affected by or are at risk of agricultural drought. This factsheet provides a brief technical description of the version 3.0.0 (hereafter, v3) update of the CDI as implemented in the Copernicus European Drought Observatory (EDO).

The spatial and temporal scale, the geographic coverage and the input variables for the calculation of the CDI are summarised in the table below.

Variables	Temporal scale	Spatial scale	Coverage
Precipitation, soil moisture, and vegetation response.	10 days	5 km	Europe

1. Brief overview of the indicator

The CDI is an indicator for drought early warning, specifically designed to monitor agricultural drought. Through the combination of spatial patterns of precipitation, soil moisture and greenness vegetation anomalies, the CDI identifies areas at risk of agricultural drought, areas where the vegetation has already been affected by drought and areas in the process of recovery to normal conditions. Accordingly, the CDI classification scheme defines three primary drought classes ("Watch", "Warning" and "Alert") and three recovery classes ("Temporary Soil Moisture recovery", "Temporary vegetation recovery" and "Recovery"). The CDI version 2.0.0 (hereafter, v2) has been developed by Cammalleri et al. (2021), following the work of Sepulcre-Canto et al. (2012). The European Drought Observatory released the CDI v3 update in March 2023. This revision mainly benefits from the incorporation of time-varying crop masks, which prevent the use of the ALERT impact class (stress for vegetation) in crop areas out of the growing season.

2. What the indicator shows

Agricultural drought is characterized by potential reduced crop productivity due to meteorological and soil critical conditions (Mishra and Singh, 2010). The original description of the CDI in Sepulcre-Canto et al. (2012) assumes a cause-effect relationship for agricultural drought: a shortage of precipitation (the cause) leads to a soil moisture deficit that results in a reduction of vegetation productivity (the effect). In order to partly address the complex and nonlinear relationship between precipitation, soil moisture and vegetation anomalies, Cammalleri et al. (2021) proposed a revision of the indicator (CDI v2) with an improved classification scheme. This one is presented in Table 1, where a color[1] identifies each CDI level to facilitate its interpretation and communication. Note, the increasing drought severity from Watch to Alert is represented through warm colors (yellow, orange, red), a common convention for signaling danger levels (Verpe Engeset et al., 2022).

	LEVEL	*INTERPRETATION*
0	***No drought***	Normal conditions
1	***Watch***	Precipitation deficit
2	***Warning***	Negative soil moisture anomaly, usually linked with precipitation deficit
3	***Alert***	Negative anomaly of vegetation growth, usually linked with precipitation deficit and negative soil moisture anomaly
4	***Recovery***	After a drought episode, both meteorological conditions and vegetation growth return to normal
5	***Temporary Soil Moisture recovery***	After a drought episode, soil moisture conditions are above the drought threshold but not enough to consider the episode closed
6	***Temporary vegetation recovery***	After a drought episode, vegetation conditions are above the drought threshold but not enough to consider the episode closed
7	***No data***	No data

Table 1*. The CDI drought classification scheme.*

[1] CDI v3 uses a scientific colour palette elaborated by Okabe and Ito (2008), extended with the red colour in order to highlight the Alert class and improve CDI visual inspection through the EDO website.

3. How the indicator is calculated

The CDI combines anomalies of precipitation, soil moisture and vegetation greenness. More specifically, the CDI uses the following three drought indicators implemented in EDO:

- **Standardized Precipitation Index** (SPI): This indicator measures precipitation anomalies at a given location, based on a comparison of total precipitation amounts for a defined accumulation period (e.g., 1, 3, 6, 9, 12, 48 months), with the long-term historic precipitation record for the same period (McKee et al., 1993; Edwards and McKee, 1997).
  Both the one-month (SPI-1) and three-month (SPI-3) variants are included in the elaboration of CDI. As for SPI-3, several studies have shown that it has the strongest correlation with the vegetation response and is, therefore, the most suitable for identifying agricultural drought (e.g., Ji and Peter, 2003; Rossi and Niemeyer, 2012). In contrast, SPI-1 can detect extreme short-term dryness that can affect the vegetation condition depending on its stage of development.
- **Soil Moisture Anomaly:** This indicator is derived from anomalies of estimated daily soil moisture (or soil water) content, represented as standardized soil moisture index (SMI). The SMI is a product from the JRC LISFLOOD hydrological model (de Roo et al. 2000; Laguardia and Niemeyer, 2008).
- **fAPAR Anomaly**: fAPAR represents the fraction of incident solar radiation that is absorbed by land vegetation for photosynthesis. Analyzing the impact of the 2003 drought on different land cover types in Europe, Gobron et al. (2005) have shown that satellite-derived fAPAR anomalies are a reliable variable for detecting and assessing drought impacts on vegetation canopies.

The following principles are applied to construct the CDI indicator:

- In accordance with the SPI classification of McKee et al. (1993), “moderate drought” conditions for SPI-3, fAPAR Anomaly and SMA are captured using a threshold of minus one (-1) standard deviation.
- Conversely, a threshold of minus two (-2) standard deviations is used for the SPI-1, corresponding to “extreme drought” conditions.
- In order to enhance the temporal consistency of the CDI in the assessment of drought, its history (CDI level in the previous 10-day period) is also considered.
- Following Cammalleri et al. (2021), the CDI v3 implements a temporal constraint on the two “Temporary recovery” classes. This constraint fixes the maximum duration of the Temporary recovery stages at four consecutive 10-day periods.
- The CDI v3 update introduces some additional thresholds (see Section 5) on the precipitation, soil moisture and fAPAR anomalies, without affecting either the original conceptual framework of the CDI nor its overall performance.
- fAPAR anomalies from crop fields out of the growing season are masked with the use of crop spatial masks. In this case, the CDI is calculated by combining only precipitation and soil moisture anomalies.

4. CDI conceptual framework

Table 2a provides a schematic representation of the CDI v3 computation procedure. Here, zSM and zfAPAR indicate anomalies of Soil Moisture and fAPAR, respectively; zSPI is a Boolean indicator equal to 1 when either SPI-1 or SPI-3 reports a dry status (i.e., SPI-1≤-2 or SPI-3≤-1), otherwise equal to 0. To determine the actual level of the CDI, the piece of information (the combination of zSPI, zSM and zfAPAR) provided by each column must be integrated with the knowledge of the CDI level in the previous 10-day period (CDI_{d-1}, the row names on the left side of the table).

- Sometimes, it can happen that the CDI remains locked in the same class for long time as impacts can linger. For instance, consider the "Alert" and "Temporary vegetation Recovery" levels in column A. These two are triggered when: 1) in the previous 10-day period the indicator assessed a condition of (temporary recovery from) vegetation stress; 2) both zSPI and zSM do not signal abnormal conditions; 3) zfAPAR has returned above the reference threshold (zfAPAR > -1), but its values are still negative. If the situation described in point 3) persists for too long (specifically, 4 consecutive 10-day periods), it is reasonable to assume that the system is gradually returning to normal pre-drought conditions and "promote" the CDI from the "Alert/Temporary vegetation Recovery" stage to a "Recovery" stage. In Table 2a, the classes assigned because of Temporary constraints are identified by an "*".

Table 2b describes the computation of the CDI when:

- fAPAR is missing (e.g., when satellite images are plagued by cloud contamination);
- fAPAR anomalies are filtered out with the use of crop mask. The application of crop masks is fundamental for a proper assessment of crop growth. The use of crop masks allows to discriminate between anomalous signals of fAPAR from exposed bare soil in crop fields and fAPAR anomalies due to drought stress on vegetation.

It is worthwhile to observe that Table 2b is the same as Table 2a but without the columns D, E, G and H. These are the columns where the vegetation response to drought is assessed (zfAPAR≤ -1). Accordingly, in Table 2b, the worst impact level is Warning.

***Table 2a**. CDI conceptual framework. The color scheme is the same as used in Table 1.*

<table>
<tr><td></td><td></td><td colspan="3">A</td><td colspan="3">B</td><td colspan="2">C</td><td>F</td></tr>
<tr><td rowspan="3">Drought indicators</td><td>zSPI</td><td colspan="3">=0</td><td colspan="3">=1</td><td colspan="2">=0</td><td>=1</td></tr>
<tr><td>zSM</td><td colspan="3">> -1</td><td colspan="3">> -1</td><td colspan="2" rowspan="2">≤ -1</td><td rowspan="2">≤ -1</td></tr>
<tr><td></td><td>≤-0.5</td><td>(-0.5;-0]</td><td>>0</td><td>≤-0.5</td><td>(-0.5;-0]</td><td>>0</td></tr>
<tr><td></td><td>CDI_{d-1}</td><td colspan="8"></td></tr>
<tr><td rowspan="5">CDI conditions in the previous 10-day period</td><td>No Drought</td><td colspan="3" rowspan="2">No Drought</td><td colspan="3" rowspan="2">Watch</td><td>No Drought
(SPI-1>0.5) AND (SPI-3>0)</td><td>Warning
!(SPI-1>0.5) AND (SPI-3>0)</td><td rowspan="5">Warning</td></tr>
<tr><td>Recovery</td><td colspan="2">Recovery</td><td colspan="2">Watch</td></tr>
<tr><td>Watch</td><td colspan="3">Recovery</td><td colspan="3">Watch</td><td colspan="2" rowspan="3">Warning</td></tr>
<tr><td>Warning/ Temporay Soil Moisture Recovery</td><td>Warning</td><td>Temp. SM R.</td><td rowspan="2">Recovery</td><td>Warning</td><td>Temp. SM R.</td><td rowspan="2">Watch</td></tr>
<tr><td>Alert/ fAPAR Recovery</td><td colspan="2">Recovery*</td><td colspan="2">Watch*</td><td colspan="3">Recovery</td><td colspan="3">Watch</td></tr>
</table>

***Table 2b**. CDI conceptual framework when: 1) fAPAR is missing; 2) fAPAR anomalies are filtered out with the use of crop masks. The color scheme is the same as used in Table 1.*

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5. How to use the indicator

Figure 1 shows the severity and extent of the drought event in March 2022 as seen by the CDI. The maps have a great deal of information and show the potential use of the CDI in an early warning system to identify and monitor areas prone to suffer drought effects. In early March, almost half of Europe (notably Italy, France and the Iberian Peninsula) was suffering from a soil moisture deficit (orange areas), while both eastern and northern Europe were experiencing normal conditions (white areas). At the end of March, the extent of drought conditions increased: the CDI classified most of Europe in Warning impact level conditions. Furthermore, the red areas in the Iberian Peninsula indicate that soil moisture drought was negatively affecting vegetation.

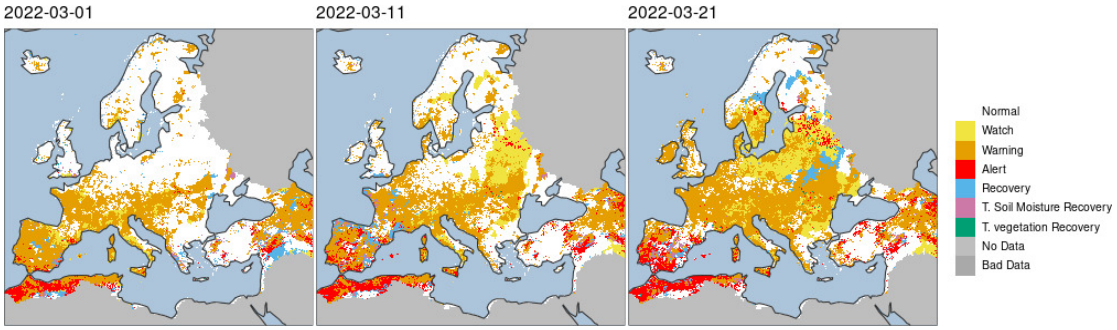

***Figure 1**. Temporal evolution of the March 2022 European drought according to the CDI-v3.*

CDI v3 introduces a new threshold (column C in Table 2a and 2b, first row), in order to modulate potential asynchronies between spatial patterns in soil moisture and precipitation/vegetation anomalies. Consider the second 10-day period of June 2021 in Figure 2. A negative signal in soil moisture anomalies was affecting Europe, especially across the Scandinavian Peninsula. At the same time, both SPI and fAPAR anomalies did not exhibit significant deviations from normal conditions in the same area (not shown). Surprisingly, the CDI v2 classifies most northern Europe as "No drought", although the precipitation anomalies are not so high to alleviate the soil moisture deficit. In contrast, the soil moisture drought is clearly visible in the CDI v3 map thanks to the new threshold in Column C.

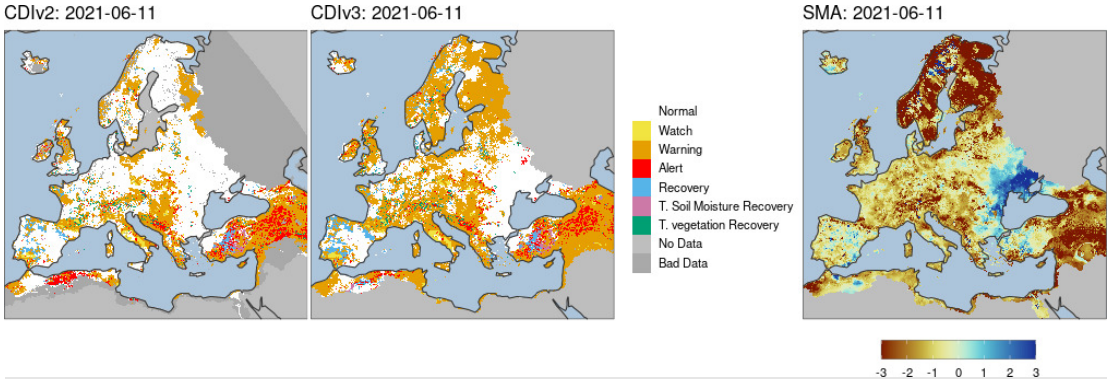

***Figure 2**. Comparison of the CDI v2 versus CDI version 3 for the second 10-day period of June 2021. The soil moisture anomalies are represented in the third map on the right.*

Figure 3 and 4 illustrate how applying crop masks in the CDI v3 provides more robust information on potential drought impacts on crops. For instance, let us consider the Italian Peninsula and Sardinia. The CDI v2 maps (Figure 3) suggest that drought was severely affecting crops (red areas) and that the extent of this dry condition was increasing over time. However, these signals disappear in the corresponding CDI v3 (Figure 4). The reason is that such signals pertain to crop fields out of the growing season and are filtered out when the crop masks are used.

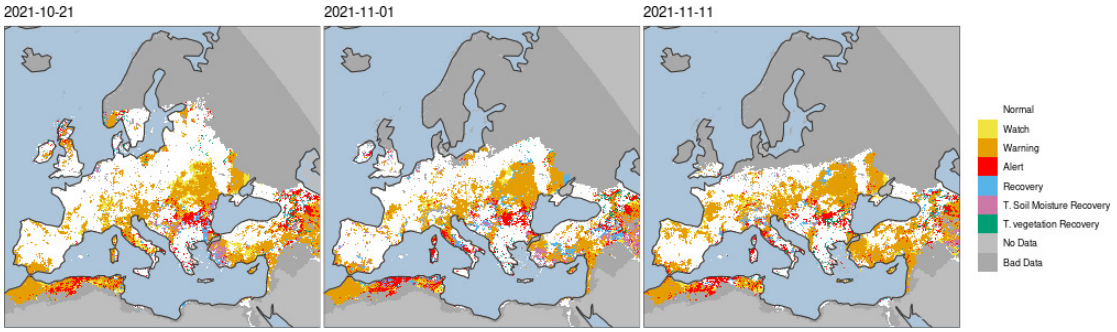

***Figure 3**. Temporal evolution of the October/November 2022 European drought according to the CDI v2. Note, the CDI v2 classifies as "Bad Data" those areas where fAPAR anomalies are missing.*

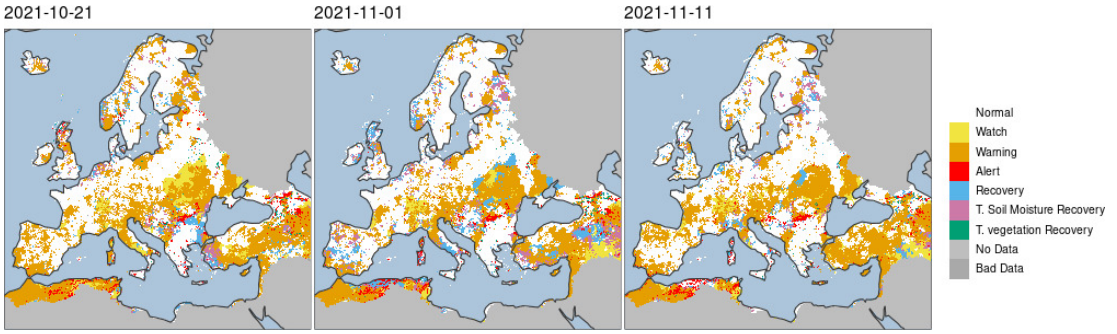

***Figure 4**. Temporal evolution of the October/November 2022 European drought according to the CDI v3. Note, in the CDI v3 when fAPAR anomalies are missing the computation is carried out by combining only precipitation and soil moisture anomalies. In this case, the worst impact level is Warning.*

6. Strengths and weaknesses of the indicator

Strengths:

- By integrating information from meteorological, hydrological and remote sensing vegetation data, a combined indicator can help reduce false alarms in drought assessment. For example, a biomass reduction can be caused by factors other than drought-induced water stress.
- Evidence of drought based on an integrated approach can support policy-makers in effective risk management and decision-making.
- The use of spatial indicators of phenology (crop masks) provides more robust assessment of potential drought impacts on crops.

Weaknesses:

- The satellite-derived fAPAR Anomaly indicator is based on reflected solar radiation, with wavelengths in the optical region (i.e., visible and infrared wavelength) of the electromagnetic spectrum, and is therefore not effective in the presence of clouds. Clouds are generally masked out before the indicator is computed. However, low clouds are not always detected, resulting in erroneous indicator values. This problem is particular serious in northern Europe. One way to address this issue would be to use more than one indicator related to vegetation growth.
- The CDI signal over snow covered regions comes from a real precipitation deficit combined with a soil moisture deficit (estimated by hydrological simulations). Having snow cover for longer periods, unfortunately, negatively affects the quality of soil moisture estimations. Hydrological models currently in use need to be improved with respect to the snow dynamics. Accordingly, we are evaluating potential development projects in the medium term. In the short term, we are working on the next CDI version 3.1 with the objective of integrating also satellite snow cover data.

References

- Cammalleri, C. and Arias-Muñoz, C. and Barbosa, P. and de Jager, A. and Magni, D. and Masante, D. and Mazzeschi, M. and McCormick, N. and Naumann, G. and Spinoni, J. and and Vogt, J. 2021. A revision of the Combined Drought Indicator (CDI) used in the European Drought Observatory (EDO), Nat. Hazards Earth Syst. Sci., 21, 481–495.

- Edwards, D.C. and McKee, T.B. 1997. Characteristics of 20th Century Drought in the United States at Multiple Time Scales. Climatology Report Number 97-2. Colorado State University, Fort Collins.

- Gobron N., and Pinty, B. and Mélin, F. and Taberner, M. and Verstraete, M.M. and Belward, A. and Lavergne, T. and Widlowski, J.-L. 2005. The state of vegetation in Europe following the 2003 drought. International Journal of Remote Sensing, 26 (9): 2013-2020.

- Ji, L. and Peters, A. 2003. Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. Remote Sens. Environ., 87: 85-98.

- Laguardia, G. and Niemeyer, S. 2008. On the comparison between the LISFLOOD modelled and the ERS/SCAT derived soil moisture estimates. Hydrology and Earth System Sciences, 12, 1339-1351.

- McKee, T.B. and Doesken, N.J. and Kleist, J. 1993. The relationship of drought frequency and duration to time scale. In: Proceedings of the Eighth Conference on Applied Climatology, Anaheim, California, 17–22 January 1993. Boston, American Meteorological Society, 179–184.

- Mishra, A.K. and Singh, V.P. 2010. A review of drought concepts, Journal of Hydrology, Volume 391, Issues 1–2, 202-216.

- Okabe, M. and Ito, K. 2008. Color Universal Design (CUD), How to make figures and presentations that are friendly to Colorblind people, https://jfly.uni-koeln.de/color/ .

- Rossi, S. and Niemeyer, S. 2012. Drought Monitoring with estimates of the Fraction of Absorbed Photosynthetically-Active Radiation (fAPAR) derived from MERIS. In: Wardlow, B., M. Anderson, and J. Verdin (Editors). Remote Sensing for Drought: Innovative Monitoring Approaches. CRC Press, and Taylor and Francis, Boca Raton, FL, USA. Pages 95-116.

- Sepulcre-Canto, G. and Horion, S. and Singleton, A. and Carrão, H. and Vogt, J. 2012. Development of a Combined Drought Indicator to detect agricultural drought in Europe. Natural Hazards and Earth System Sciences, 12, 3519-3531.

- Engeset, R. V. and Pfuhl, G. and Orten, C. and Hendrikx, J. and Hetland, A. 2022. Colours and maps for communicating natural hazards to users with and without colour vision deficiency, International Journal of Disaster Risk Reduction, Volume 76.

Indicators

- **Standardized Precipitation Index (SPI)**:
  https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_spi.pdf
- **Soil Moisture Anomaly**:
  https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_soilmoisture.pdf
- **fAPAR Anomaly**:
  https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_fapar.pdf
- **Crop masks**:
  https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_crop_masks.pdf