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To cite this article: Lorenzo Villani *et al* 2026 *Environ. Res.: Climate* **5** 022001

IOP Publishing Environ. Res.: Climate 5 (2026) 022001 https://doi.org/10.1088/2752-5295/ae583c

ENVIRONMENTAL RESEARCH
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RECEIVED
23 December 2025

REVISED
20 February 2026

ACCEPTED FOR PUBLICATION
27 March 2026

PUBLISHED
23 April 2026

TOPICAL REVIEW

Neglecting plant physiology: systematic overestimation of drought projections

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Keywords: plant physiological response, atmospheric evaporative demand, potential evapotranspiration, CO_2 fertilization effect, stomatal resistance, standardized precipitation evapotranspiration index, palmer drought severity index

Supplementary material for this article is available online

Abstract

The impact of climate change on droughts is typically attributed to rising temperatures and altered precipitation patterns. Yet, most drought projections overlook a major climate-induced mechanism: the effect of elevated CO_2 on plant physiology, leading to a significant potential overestimation of droughts magnitudes and impacts. In fact, elevated CO_2 enhances biomass production and reduces stomatal conductance, thereby increasing water-use efficiency. Our systematic review reveals that nearly 90% of evapotranspiration-based drought projections omit CO_2-driven vegetation feedback, and only 10% acknowledge this limitation. Neglecting vegetation response to CO_2 can overestimate future drought-affected areas by up to 17.4% $\pm$ 10.6% under high-emissions scenarios (CO_2 > 900 ppm), and in some regions even reverse the projected direction of change. This widespread oversight can hamper the robustness of global drought projections. Accounting for vegetation–CO_2 interactions is therefore crucial to avoid systematic bias and produce reliable predictions of water availability in a warming world.

1. Introduction: the misalignment between offline drought projections and climate model outputs

Droughts are extremely complex hazards with subtle, indirect and delayed impacts on multiple sectors (Hagenlocher *et al* 2023, Van Loon *et al* 2016a, 2016b). To delve into this complexity, scholars typically divide drought into meteorological, agricultural, hydrological and socioeconomic drought (Mishra and Singh 2010). As a result, a plethora of indices are available to estimate drought characteristics based on multiple climatological or hydrological variables (Damkjaer and Taylor 2017, Kchouk *et al* 2022). By far, the most considered flux in the hydrological cycle is precipitation, and the most-applied drought index is the standardized precipitation index (SPI) (McKee *et al* 1993, Kchouk *et al* 2022). Nevertheless, with the increased availability and accessibility of data, also due to the emergence of remote sensing and re-analysis products, dozens of indices have been proposed which include variables other than precipitation (Zargar *et al* 2011, Han and Singh 2023). The atmospheric evaporative demand (AED), also referred to as reference (ETr; DeJonge *et al* 2025) or potential evapotranspiration (PET[11]; Brutsaert 1982) is often considered in drought monitoring and assessment. When studying future climate, it is recommended to also contemplate temperature-related variables so that global warming can be properly taken into account (Vicente-Serrano *et al* 2010, Tramblay *et al* 2020). Hence, many indices have been developed to estimate drought considering AED. The most common ones are the palmer drought severity index (PDSI, Alley 1984), that estimates soil moisture anomalies using a simplified water-balance model accounting for AED, and the standardized precipitation evapotranspiration index (SPEI, Vicente-Serrano *et al* 2010), that quantifies drought by combining precipitation and AED. The choice of the index is an important source of uncertainty, as the outcomes of drought analyses often drastically differ when using alternative indices (e.g. Vicente-Serrano *et al* 2015, Stagge *et al* 2017, Spinoni *et al* 2021, Laimighofer and Laaha 2022).

The most common evapotranspiration-based drought indices such as SPEI and PDSI quantify drought using a simplified climatic water balance between precipitation (water supply) and atmospheric water demand (Vicente-Serrano *et al* 2010). However, a variety of empirical and physically based approaches exist to calculate AED based on different sets of climatic input variables (Allen *et al* 1998, Beguería *et al* 2014, Vicente-Serrano *et al* 2015, Vicente-Serrano *et al* 2020b). It has been shown that computing future AED with methods such as Hargreaves, Thornthwaite and Penman-Monteith yields highly different results (Dewes *et al* 2017, Milly and Dunne 2017, Lemaitre-Basset *et al* 2022a). In particular, empirical approaches that rely on air temperature as a surrogate for surface radiation (e.g. the Hargreaves and Thornthwaite methods) may lose validity under CO_2 concentration changes (Milly and Dunne 2017). Furthermore, AED is commonly estimated with methods based on fixed atmospheric CO_2 levels. However, rising CO_2 concentrations influence plant behaviour in complex ways, which are not yet fully understood (Long *et al* 2004, Ainsworth and Long 2005, Fatichi *et al* 2016). Hence, even more advanced methods for estimating AED, such as Penman–Monteith, can yield inaccurate values if increases in stomatal resistance are not accounted for (Milly and Dunne 2017). Qiu *et al* (2025) comprehensively summarized the effects of elevated CO_2 on plant's evapotranspiration as: (a) reduction of stomatal conductance and therefore transpiration; (b) promotion of growth and leaf area and hence increase transpiration; (c) reduction of incident radiation and, consequently, evaporation at the soil surface; (d) promotion of root growth and, therefore, increased water uptake; (e) reduction of evaporative cooling and hence warmer canopy temperature and higher vapour pressure deficit. Despite being mostly ignored in AED calculations, several approaches exist to consider vegetation response to increased CO_2 concentrations (Sabot *et al* 2022, Chitsaz *et al* 2023). Nevertheless, reflecting the complexity of the vegetation response to CO_2, the results largely diverge (Lemaitre-Basset *et al* 2022b). As an additional layer of uncertainty, existing adjustments for CO_2–vegetation response focus mainly on reductions in stomatal conductance, while other important consequences—such as increases in leaf area—are often neglected (Liu *et al* 2023, Shen *et al* 2024).

When analysing future drought with simple climate-based metrics, like SPEI and PDSI, earth system models (ESM) outputs such as temperature, relative humidity, wind speed and solar radiation are often used to compute AED[12], since ESM do not provide AED variables. However, offline drought assessment may neglect vegetation response to CO_2 while current ESM account for this effect. Past research shows that the outcomes of offline drought analyses performed with evapotranspiration-based indices often depict a much drier future in comparison to ESM outputs (Roderick *et al* 2015, Swann *et al* 2016, Berg *et al* 2017, Berg 2022). Acknowledging that ESM simulation of vegetation response to CO_2 remains prone to uncertainties and improvements (Rogers *et al* 2017, Vicente-Serrano *et al* 2020b, Green *et al* 2024), there is consensus that the neglect leads to altered simulations of hydrological and climatic variables, such as runoff (Lemordant *et al* 2018, Lemaitre-Basset *et al* 2022b) and evapotranspiration (Greve *et al* 2019, Scheff 2019, Yang *et al* 2019, 2023) and, as a direct consequence, drought (Tramblay *et al* 2020). Nevertheless, some studies demonstrated that this effect might not be the dominant one (Scheff *et al* 2021), suggesting additional causes of overestimation and increasing the uncertainty (Vicente-Serrano *et al* 2022a).

While the influence of vegetation response to CO_2 in mitigating drought projections is acknowledged, the quantification of such underestimation is surprisingly missing. Neglecting vegetation response to CO_2 is a methodological gap that poses a risk to the credibility of climate change projections—whose adverse consequences are well recognized and do not require exaggeration. By systematically reviewing

[11] The term 'potential evapotranspiration' is widely used in drought projections, but it is confusing and its use is not recommended (DeJonge *et al* 2025). In this study, we use the term AED as done by Vicente-Serrano *et al* (2020b).

[12] These studies are generally referred to as offline drought analysis.

existing drought projection studies, this research aims to reveal the extent to which the drought literature overlooks the vegetation response to CO_2 and to quantify the resulting overestimation of drought projections. More specifically, we delve into the drought literature to verify four hypotheses: (1) vegetation response to CO_2 is not explicitly included in most drought projections; (2) vegetation response to CO_2 is generally not mentioned as a limitation or uncertainty; (3) few of the many available approaches are used to account for vegetation response to CO_2; (4) neglecting vegetation response to CO_2 causes a significant, non-negligible drought overestimation. We do this by first systematically reviewing 174 studies that assess future drought with evapotranspiration-based indices to verify if vegetation response to CO_2 is considered. After that, we quantify the overestimation extent through a meta-analysis based on a subset of papers that quantify changes in drought projections considering vegetation response to CO_2. Then, we discuss limitations and additional research gaps not addressed in this study. Finally, we conclude by providing recommendations to improve our understanding of vegetation response to CO_2 and their implications for the validity of future drought assessments.

2. Methods

The process to verify the four hypotheses is illustrated in figure 1. With the first literature review—referred to also as the systematic literature review—hypotheses 1, 2 and partially 3 were verified. Then, with the second literature review—referred to as the meta-analysis—additional studies were identified. These studies were used to evaluate the remaining hypotheses. The PRISMA methodology for systematic reviews (Page *et al* 2021) was followed by considering four phases for each literature review: (1) identification, (2) screening, (3) analysis and (4) discussion.

2.1. Identification

For the systematic review, the query was performed by combining synonyms of 'drought', 'evapotranspiration' and 'climate change' in the SCOPUS database up to March 2024 using the following string:

> SCOPUS string query: (TITLE ("climate change") OR TITLE (warming) OR KEY ("climate change") OR KEY (warming)) AND (TITLE (evapotranspiration) OR TITLE (evaporation) OR KEY (evapotranspiration) OR KEY (evaporation)) AND (TITLE (drought) OR KEY (drought))

Given that the main objective of the second literature study was to analyse the manuscripts that discuss the inclusion of vegetation response to CO_2, additional relevant publications were searched through a snowball approach. A set of key references that introduced approaches to include vegetation response to CO_2 in the calculation of AED (table S1) was then identified. Finally a search of the words 'drought', 'climate change' and 'future' within the papers that cite (a subset of) the key references was performed in Google Scholar. This second search was performed considering manuscripts available on the web search engine up to December 2024.

2.2. Screening

In the systematic review, the identified records were screened and evaluated according to the following exclusion criteria, by focusing mainly on the title and abstract of the publications and, if necessary, by a quick screening of their full text. Publications were excluded if:

- They are not written in English.
- They are not the correct type of paper (notes, letters, errata and short surveys). Hence, conference papers and articles are mainly considered. Reviews are not automatically excluded but are evaluated for the discussion, if relevant to the topic.
- They are not considering the future in the analysis.
- They are not explicitly assessing future drought periods, but for instance, focus only on water balance components, evapotranspiration and aridity trends.
- Future drought is not assessed with an evapotranspiration-based index. Hence, for example, drought projections based solely on SPI are excluded.

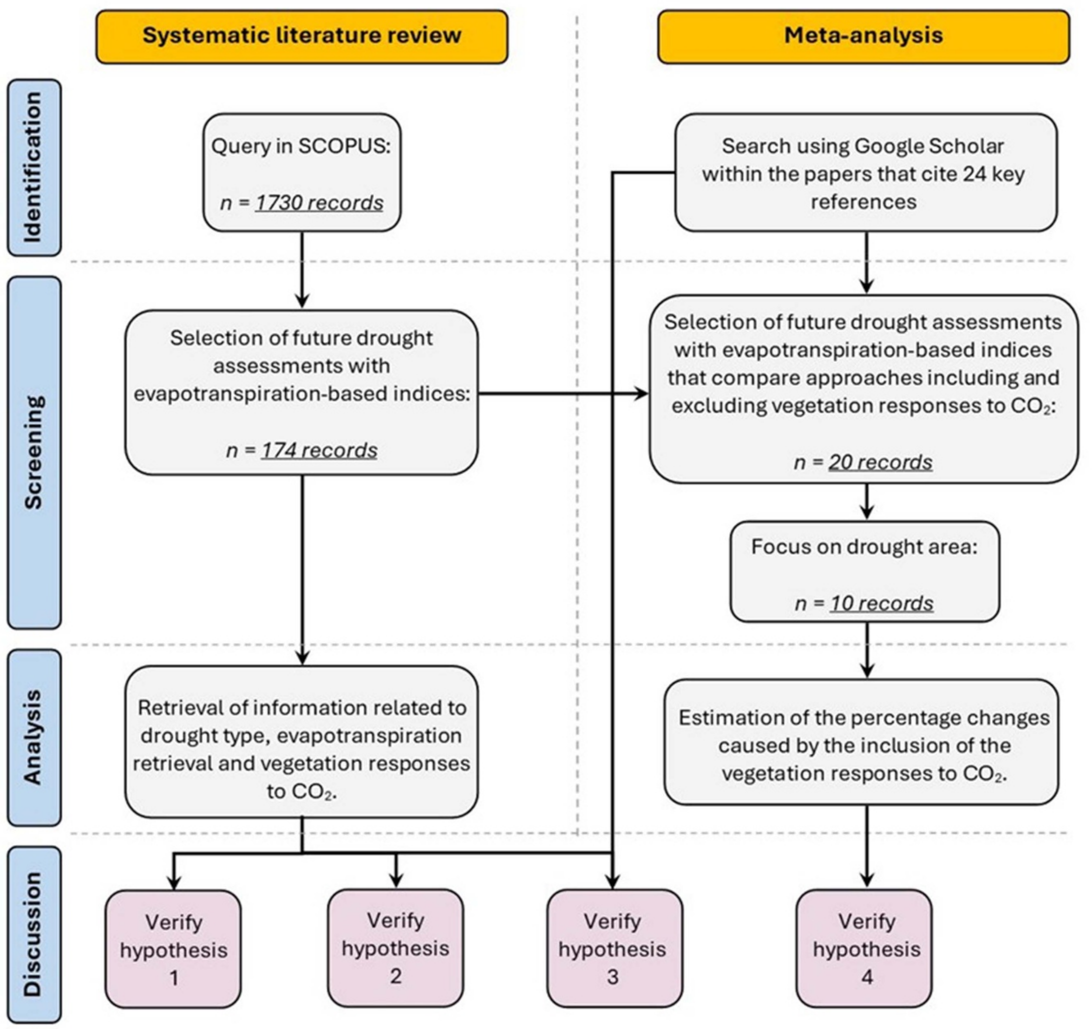

Figure 1. The complete methodology used in the systematic literature review and meta-analysis parts of the research with the four phases of the PRISMA methodology.

The same exclusion criteria applied for the records of the meta-analysis. Finally, only those papers that estimate future drought by comparing approaches both with and without considering the vegetation response to CO_2 were selected for the analysis.

2.3. Analysis

In the systematic review, information from every selected publication was extracted to verify the first, second and partially the third hypotheses. The information retrieved, aggregated and then synthesized from each record included the year of publication, the type of drought considered, the evapotranspiration method used and whether or not vegetation response to CO_2 is included in the analysis and mentioned in the text. The full list of data collected with a detailed explanation is reported in table S2.

The second phase consisted in an in-depth analysis of the manuscripts that include the vegetation response to CO_2 and those additionally identified through the search in Google Scholar. The additional records served also to complete verifying hypothesis 3. To verify hypothesis 4, all those manuscripts that compare future droughts estimated with and without the consideration of the vegetation response to CO_2 were carefully assessed. A key characteristic of the papers to be included in the meta-analysis was that they explicitly study the issue and discuss related results, either quantitatively or qualitatively. Hence, publications that directly compare different AED estimation methods or use the same approach but with constant or increased CO_2 concentration were mainly considered. For example, studies that compared drought evapotranspiration-based indices with soil moisture-based ones derived from ESM—that often consider the vegetation response—were excluded. Such relevant papers are mentioned when discussing the results. Given the importance of the study, in the meta-analysis, the paper of Swann *et al* (2016) that quantifies the changes caused by the inclusion of vegetation response to CO_2 by comparing PDSI and precipitation minus evapotranspiration was also included. Finally, manuscripts that discuss the effect of vegetation response to CO_2 by using the outputs of global hydrological models from ISIMIP that, for some setups, contemplate these effects, were also considered.

Unfortunately, it was not possible to collect quantitative data from all the selected papers to quantify the bias related to the vegetation response to CO_2; some of the studies did not provide explicit drought estimates but only drought indices and related trends. Furthermore, the papers evaluated different drought characteristics, such as drought area, frequency, severity, intensity and so on. Only a few papers explicitly calculated the percentage changes, while others just reported general considerations. In the latter case, if possible, the absolute or percentage changes were extracted from the figures by using plotdigitizer.com/app. While some papers directly reported the CO_2 concentration values, most of them relied on representative concentration pathways (CMIP5) and shared socioeconomic pathways (CMIP6). When CO_2 concentration was not explicitly reported, the corresponding CO_2 concentration value in the years of analysis as reported in Meinshausen *et al* (2011), Meinshausen *et al* (2020) for CMIP5 and CMIP6 respectively were used. Since the search yielded a very reduced number of studies, all the available studies were considered without introducing any further selection criteria.

To verify hypothesis 4, the overestimation extent was calculated for three ranges of CO_2 concentrations: low emissions ($CO_2 < 400$ ppm), intermediate emissions (500 ppm $< CO_2 <$ 600 ppm) and high emissions ($CO_2 > 900$ ppm). We averaged all the data points for each paper per scenario, before retrieving the final value. To verify the robustness of this estimation, the values were retrieved also considering only the global and regional studies. Furthermore, the values without averaging all the data points for each paper were calculated and reported in the supplementary materials.

3. Results

3.1. Vegetation response to CO_2 in drought projections—insights from the systematic review

After a first screening of 1730 papers using the search described in the methods section, 174 of them were analysed. The number of drought projections (figure 2(b)) with evapotranspiration-based indices rapidly surged some years after the introduction of the SPEI in 2010 (Vicente-Serrano *et al* 2010), while only one publication was found for the period before 2004 (Rind *et al* 1990).

The systematic review indicates a predominance of high-emissions scenarios, followed by intermediate and low-emissions pathways (table S3), with most studies including as study period the end of the century (table S4). Analyses are conducted primarily at national and subnational scales, whereas global assessments remain comparatively rare (table S5). Overall, 28 countries across four continents are represented, with China and Asia emerging as the most frequently studied country and continent, respectively (figure 2(a); table S6). Meteorological drought is the most commonly assessed type, followed by hydrological and agricultural droughts, while a substantial fraction of studies does not explicitly specify the drought category (table S7). In most cases, evapotranspiration is computed directly within the study, and vegetation response to CO_2 is generally not incorporated (table S8). Among evapotranspiration-based indices, SPEI clearly dominates, followed by PDSI (figure S2), and precipitation is by far the most frequently hydrological variable combined with AED (figure S3). Penman–Monteith is the most widely used method to estimate AED, followed by Thornthwaite and Hargreaves (figure S4).

Out of 174 studies, only 14 (8%) include vegetation response to CO_2 in the assessment of future drought (figure 2(b), table S8). Seven additional papers may have considered them since they cited key literature but do not explicitly mention vegetation response to CO_2 (figure 2(c), table S8). Therefore, the percentage of papers that explicitly consider the vegetation response to CO_2 ranges from 8%–12% of the total. Even after key publications such as Roderick *et al* (2015), Milly and Dunne (2016), Swann *et al* (2016) and Yang *et al* (2019), the consideration of the topic is still relatively low. In the period 2020–2024, only 16 out of 110 drought assessments (15%) include vegetation response to CO_2 (figure 2(b)).

Not only the direct inclusion of the vegetation response to CO_2 is low, but only a small share of publications mention them as a limitation or a source of uncertainty. Only 18 studies (12%)—among those that did not directly and clearly include vegetation response to CO_2—somehow mentioned the limitation or uncertainty or cited related key literature (figure 2(b), table S8). It is important to underline that, in the systematic review, 91 out of 156 papers (57.5%) that did not include vegetation response to CO_2 considered high emission scenarios by the end of the century with $CO_2 > 900$ ppm

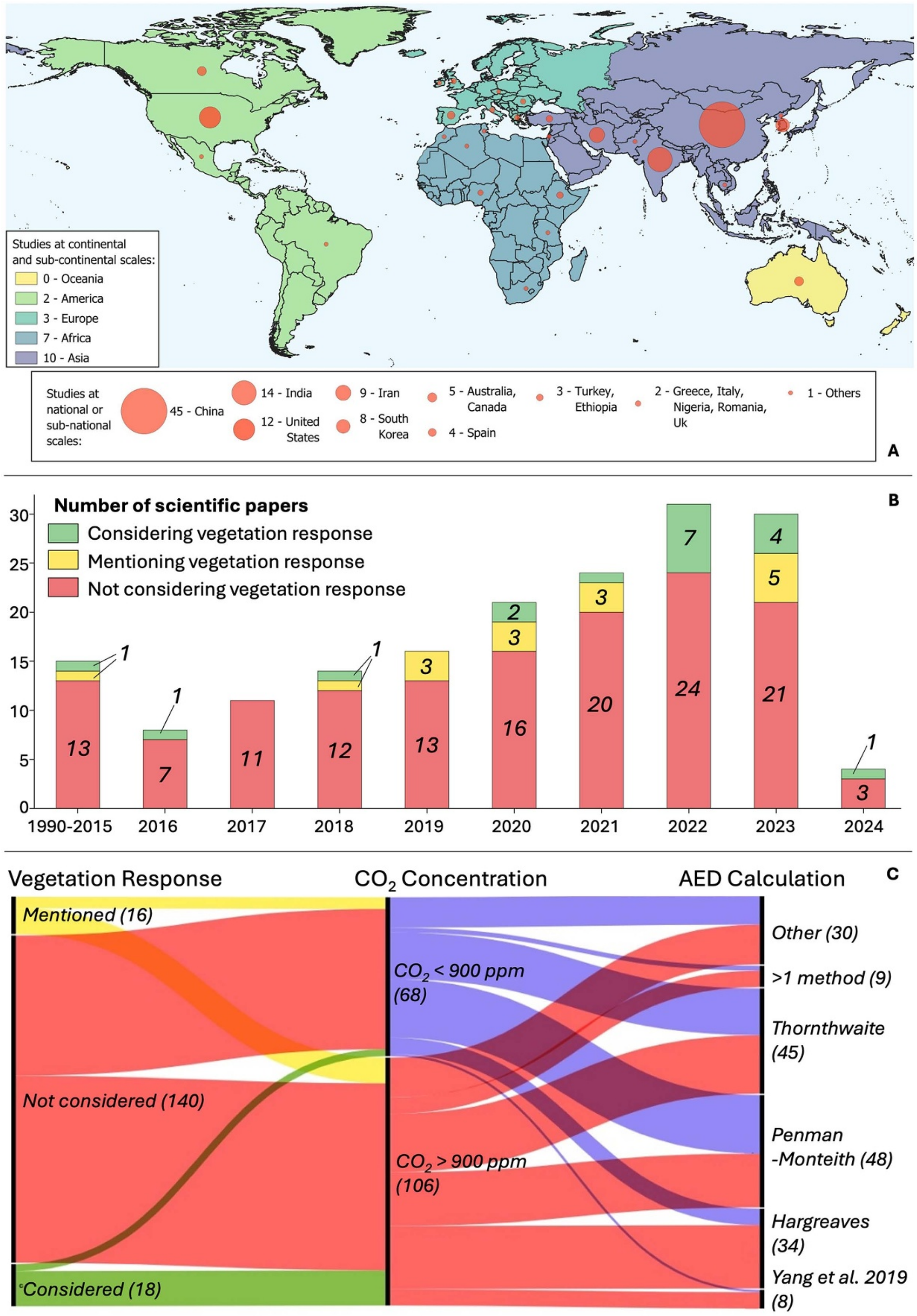

Figure 2. Outcomes of the systematic literature review. (A) The distribution of the studies included in the systematic review at (sub)continental scale—represented with categorized colours—and (sub)national scale—represented with dimensions of the red dot. (B) Year of publication of the papers considered in the systematic review phase (the search was performed in March 2024) with the number of papers that either include—meaning that they used a modified AED retrieval method—or mention—i.e. they discuss the limitations or they refer to key references—vegetation response to CO_2. (C) Alluvial plot[13] to show the number of papers that consider and mention vegetation response to CO_2, whether they consider elevated CO_2 concentration scenarios and the method to retrieve AED. Notice that numbers are slightly different from the text as in the figure the unclear studies were assigned to the most likely category ('considered', 'mentioned').

(figure 2(c)). Among them, 28 apply the Thornthwaite method to estimate future AED that, being highly sensitive to increased temperatures, drastically overestimates future AED and hence drought (Milly and Dunne 2017, Aadhar and Mishra 2020, 2022). Even if the mechanisms and processes behind the

[13] The plot was created in rawgraphs.io.

vegetation response to CO_2 are still debated (e.g. Vicente-Serrano *et al* 2022a), the literature suggests that avoiding their inclusion leads to an overestimation of AED and drought (Roderick *et al* 2015, Swann *et al* 2016, Berg *et al* 2017, Berg 2022). Therefore, the vast majority of the drought assessments that considered evapotranspiration-based drought indices overestimated future drought.

Another key insight is that most studies considering vegetation response to CO_2 use the simple linear modification of the Penman–Monteith equation as proposed by Yang *et al* (2019) (figure 2(c)). The second most adopted approach is the energy-based one proposed by Milly and Dunne (2016). An *et al* (2024) applied the procedure suggested by Kim *et al* (2021b, 2023b) which is improved compared to Yang *et al* (2019) as it takes into account the land-atmosphere feedback. Similarly, Shen *et al* (2024) considered the approach proposed by Liu *et al* (2023), which represents an advancement since it considers vegetation changes by incorporating the leaf area index. Li *et al* (2023b) expressed the concern that the linear equation of Yang *et al* (2019) considers only the reduction in stomatal conductance caused by increased CO_2 but disregards vegetation dynamics. To verify the extent of the uncertainty related to this simplification, they compared the canopy conductance estimated with the empirical statistical model of Yang *et al* (2019) with an optimal model and found positive correlations, especially in the middle-high emissions scenarios over most global land. Another way to include vegetation response to CO_2 in drought projections is by avoiding directly calculating AED but instead relying on external data or software. In this way, some studies indirectly consider vegetation response to CO_2 response by using outputs from ESM (e.g. Burke and Brown 2008, Burke 2011, Cook *et al* 2015, Zhao and Dai 2015, 2022, Swann *et al* 2016, Vicente-Serrano *et al* 2022b) or global hydrological models from ISIMIP (e.g. Satoh *et al* 2022, Wang *et al* 2022a) or other crop or hydrological models such as the soil and water assessment tool (SWAT, e.g. Li *et al* 2023a, Villani *et al* 2024) and the simulation of evapotranspiration of applied water (SIMETAW, e.g. Mancosu *et al* 2016, Masia *et al* 2021).

3.2. The effect of vegetation response to CO_2 on drought projections—insights from the meta-analysis

Building on the first part of the analysis, which evaluated the share of drought projections neglecting vegetation response to CO_2, the second part considers a subset of records to quantify the resulting bias. After having completed the second search, only the 20 publications that directly compare drought projections considering both cases of including/excluding the vegetation response to CO_2 were selected. However, many studies investigate different drought attributes and are therefore difficult to compare. Finally, the quantification was based on the changes in projected drought area due to the inclusion of vegetation response to CO_2 considering 10 publications (table S9, figures 3(a) and (c)). The literature analysed agrees that disregarding the vegetation response to CO_2 leads to an overestimation of future drought area (figures 3(d) and S5). Most of the changes (86%) are above −20% and feature a fairly extensive range with a minimum of −42.6% (figure 3(d)). Most of the outliers are the data points extracted from study 2—Jiang *et al* (2022b) that also for the historical period found unusual reductions below −30% caused by the inclusion of the vegetation response to CO_2. A possible explanation for this could be that their study area (i.e. the Chinese drylands) is more sensitive to AED changes (as in study 1—Aadhar and Mishra 2020). The data point collected from study 6—Swann *et al* (2016) is another outlier, with an estimated change of −33% at elevated CO_2 concentration. Notably, this study differs from the others by estimating drought area using PDSI without vegetation response to CO_2 and precipitation minus evaporation when accounting for it. Study 1—Aadhar and Mishra (2020) also found a substantial change for hyper-arid South Asia for which the change reaches −34%, in line with the values of study 2—Jiang *et al* (2022b). Analysing in detail the outputs of study 1—Aadhar and Mishra (2020), it is evident how climate type strongly influences the effect of the vegetation response to CO_2; while large sensitivities are found in hyper-arid and arid climate zones, the changes are limited to approximately 3% for the humid climate. In addition to study 2—Jiang *et al* (2022b), study 10—Wang *et al* (2022a) reported high historical changes of 5.8%–9.4%, depending on the drought severity threshold. Specifically, study 10—Wang *et al* (2022a) used the outputs of ISIMIP global hydrological models and compared them with the standard PDSI index, suggesting that the vegetation response to CO_2 is not the only difference in the models. Except for these studies, in the group with historical CO_2 concentrations, the differences are below 2.4% for study 7—Yang *et al* (2020), study 4—Kim *et al* (2021a) and study 3—Jiang *et al* (2022a), while they are negligible considering all the outputs from study 1—Aadhar and Mishra (2020) and study 5—Kim *et al* (2023a). As expected, they increase in the future as CO_2 concentration rises.

As reported in table S14, the effect of neglecting vegetation response to CO_2 in the estimation of future drought area is quantified in 6.0% ± 11.3%, 8.7% ± 11.0% and 17.4% ± 10.6% for the historical (CO_2 < 400 ppm), intermediate (500 ppm < CO_2 < 600 ppm) and high emissions scenarios (CO_2 > 900 ppm) respectively (figure 3(d)). The other options that were considered to estimate the bias yield similar results (tables S11–16). More specifically, comparing global (studies 6–10) and regional

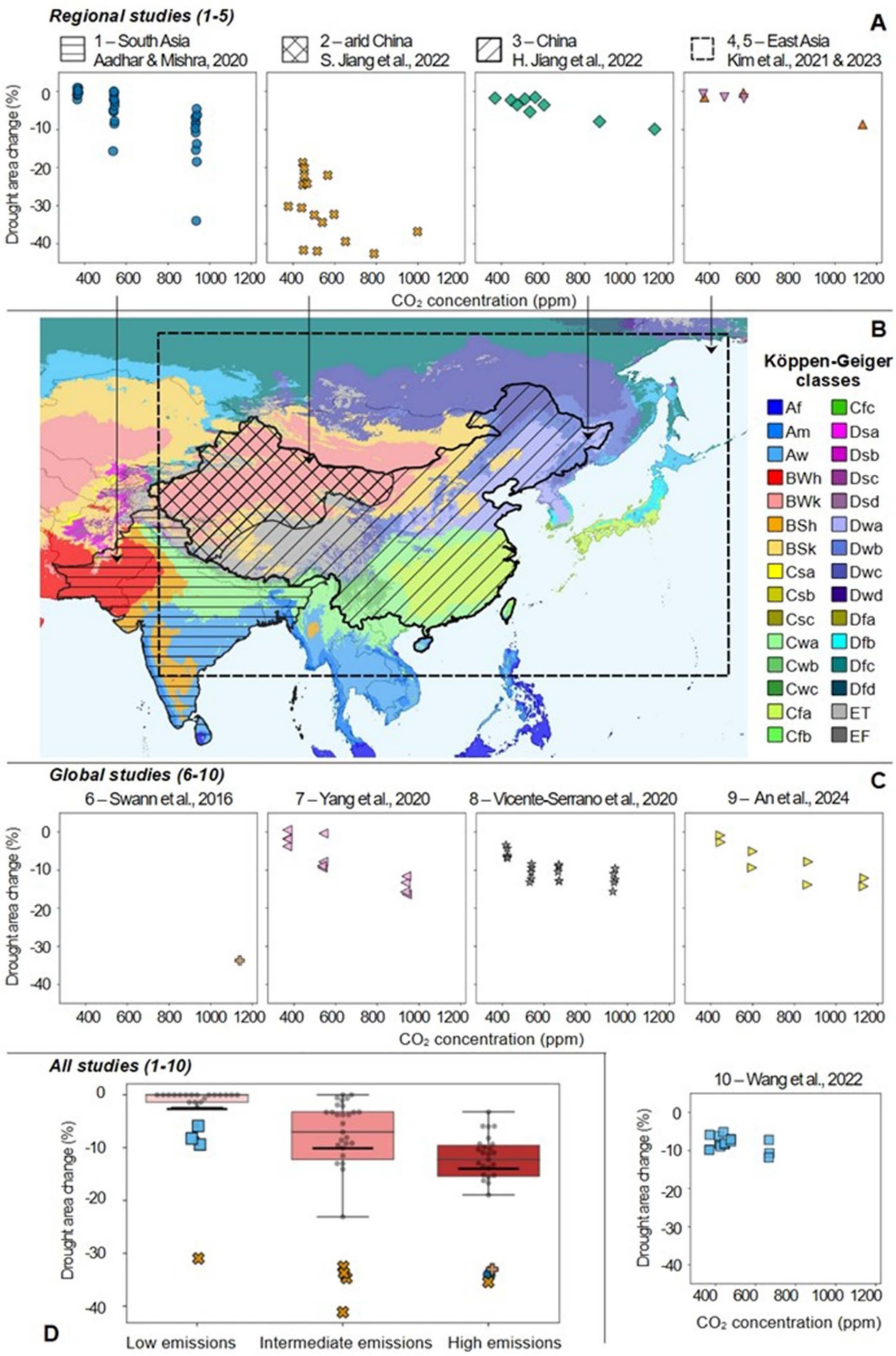

Figure 3. Outcomes of the meta-analysis. (B) The map of South and East Asia represents the study area of the five regional publications (table S9) used in the meta-analysis, with the Köppen–Geiger climate classification from Beck *et al* (2018) as background. (A) The first row of scatterplots refer to the five regional studies; (C) under the map are reported the scatterplots of the five global studies and (D) a box plot summarising the results of all the studies. Each scatterplot represents the estimated percentage changes in drought area against CO_2 concentration (ppm) caused by the inclusion of the vegetation response to CO_2. Data entries from different sources are coloured and marked differently. For each paper, the data is extracted from text and figures. Note that data entries vary among the 10 publications, ranging from 1 to 36 values, as reported in table S9. The complete scatterplot is reported in the supplementary materials (figure S5). The box plot considers the same data but grouped to consider the historical (CO_2 < 400 ppm), intermediate (500 ppm < CO_2 < 600 ppm) and high emissions (CO_2 > 900 ppm) CO_2 concentration levels. Grey dots represent the data while the horizontal black bar the average values. The outliers from study, 1, 2, 6 and 10 have the same formatting as in the scatterplots. Study 8 corresponds to the reference Vicente-Serrano *et al* (2020a). (b) Reproduced from Beck *et al* (2018).

(studies 1–5) papers results in differences in changes below 2%, though a higher standard deviation is observed for the regional studies (tables S13 and S16). Considering the average of the papers instead of all the data points of table S9 results in higher biases for the low and high emissions scenarios (tables S11 and S14). This is mostly caused by the higher importance assigned to the data point from study 2—Jiang *et al* (2022b) and to study 6—Swann *et al* (2016) for the low and high emissions scenarios, respectively. On the other hand, the overestimation for the intermediate scenario is slightly reduced.

Analysing additional papers (table S10), different outcomes emerge, confirming the uncertainty around this topic and the range of changes reported in figure 3(d). For example, some of them found negligible changes caused by vegetation response to CO_2 (Cook *et al* 2015, Zeng *et al* 2023). However, most of the studies confirmed the overestimation of drought as a result of neglecting the vegetation response to CO_2, with consistent—yet less pronounced—changes (e.g. Lehner *et al* 2017, Ficklin *et al* 2022, Li *et al* 2023b, Su *et al* 2024, Xu *et al* 2024). Finally, a subset of studies reported not only an overestimation of drying trends after the inclusion of the vegetation response to CO_2 but also an opposite sign of change, with wetter future conditions in some parts of the study areas. For example, Sun *et al* (2024) found similar trend patterns with both cases, except in northeastern China, where including vegetation response to CO_2 reversed the signal from drying to wetting. Similarly, Shen *et al* (2024) found significant changes in southwestern China when considering vegetation response to CO_2, shifting from a drying trend with the standard Penman-Monteith equation towards negligible or wetting trends considering vegetation response to CO_2 with SPEI or PDSI, respectively. An *et al* (2024) analysed global drought patterns and trends by applying the methods of Yang *et al* (2019) and Kim *et al* (2021b, 2023b) and, at the global scale, found the strongest drying trends when using the standard Penman–Monteith approach, followed by the method of Yang *et al* (2019). Interestingly, when considering the equations of Kim *et al* (2021b, 2023b) to incorporate the vegetation response to CO_2, they found a slight wetting global trend. Focusing on smaller scales, in the same publication (An *et al* 2024), the Penman–Monteith approach proposed by Yang *et al* (2019) resulted in the opposite sign of change for 14.7% of the land, while this percentage increased to 22.6% when considering Kim *et al* (2021b, 2023b). While much more research is certainly needed, it is revealing that the two studies (An *et al* 2024, Shen *et al* 2024) that used state-of-the-art approaches in land-atmosphere feedback (Kim *et al* 2021b, 2023b) or incorporate leaf area index (Liu *et al* 2023) showed the strongest differences compared to standard Penman–Monteith—higher frequency of sign reversals compared to Yang *et al* (2019).

4. Discussion

4.1. Vegetation response to CO_2 omission as a critical methodological gap in drought projections

The neglect of vegetation response to CO_2 in evapotranspiration-based drought projections is surprising since the plant physiological effect of rising CO_2 have been extensively debated for decades in plant- and water-related disciplines (Jarvis 1976, Rind *et al* 1990, Field *et al* 1995). For example, this type of research is fully considered in the latest Assessment Report of the Intergovernmental Panel on Climate Change and in the same ESM whose outputs are used in offline drought projections (Rogers *et al* 2017). Furthermore, only a small fraction of the approaches proposed in the literature are used to simulate vegetation response to CO_2 when deriving AED (table S1, Sabot *et al* 2022, Chitsaz *et al* 2023). As new methods become available and more studies test, apply and compare them, researchers and practitioners will have access to improved and alternative methods. Incorporating vegetation response to CO_2 into AED estimates may also become increasingly straightforward, either through direct computation using tools such as PyET (Vremec *et al* 2024) or via global model outputs and datasets (e.g. Peiris and Döll 2023). Recent developments suggest that ongoing research is already exploring alternatives to the approach of Yang *et al* (2019). A major step forward would be the inclusion of AED (evspsblpot) as a standard ESM output by the modelling community (CMIP). Our systematic review clearly shows that current drought research largely neglects vegetation response to CO_2, even when using evapotranspiration-based indices that should explicitly account for them. The implications of this omission are not limited to hazard assessments: Wang and Sun (2023) showed that excluding vegetation response to CO_2 can lead to an overestimation of drought-exposed population and GDP by up to 8.5% and 6.7% by 2050, respectively.

4.2. Limitations and sources of uncertainty

Although the analysis was conducted within a transparent and reproducible methodological framework, some limitations should be acknowledged. First, we recognize that some papers that use evapotranspiration-based indices to assess future drought are not found through the proposed query (e.g. Li *et al* 2021, Spinoni *et al* 2021). Nevertheless, we assume that the identified records are representative and unbiased to answer our research questions. Second, our study focused exclusively on drought projections based on evapotranspiration-based indices, while a comprehensive evaluation of future drought should extend to the full spectrum of drought indices. For instance, drought projections that apply soil moisture indices generally incorporate vegetation response to CO_2 as they typically use direct ESM outputs (e.g. Aadhar and Mishra 2020). On the other hand, drought projections relying solely on precipitation-based indices do not explicitly account for either rising temperatures or vegetation response to CO_2. Third, the quantification of the bias associated with neglecting vegetation response to CO_2 is currently constrained by the limited number of studies adopting alternative approaches. As more research applies and compares these methods, it will become possible to evaluate more robust changes across climates, regions, indices, and drought characteristics such as frequency and severity. Despite these limitations, this assessment represents a necessary step toward fostering a more comprehensive and critical discussion of vegetation–CO_2 interactions in future drought projections.

Beyond our analysis, substantial uncertainties remain regarding the understanding and simulation of vegetation response to rising CO_2. These include feedback and synergies of elevated CO_2 with concurrent changes in future climate (i.e. temperature and drought, Kirschbaum and McMillan 2018, Swann 2018, Vicente-Serrano *et al* 2020b, Wang *et al* 2022b), as well as processes at multiple scales such as cell, leaf, canopy and above (Fatichi *et al* 2016, Matthews and Lawson 2018, Miralles *et al* 2025). Vegetation types and species respond differently to elevated CO_2 and this is rarely represented in current drought projections (Swann 2018). Many approaches exist to simulate stomatal conductance considering the vegetation functional type (Manzoni *et al* 2011, De Kauwe *et al* 2015, Zhou *et al* 2019) which might improve the reliability of drought projections. Rising CO_2 is mainly expected to influence vegetation water-use efficiency both through the CO_2 stomatal conductance suppression and the CO_2 fertilization effect on photosynthesis, which are spatially distinct (Zhang *et al* 2022). While the stomatal conductance suppression is explicitly simulated in the modifications of the Penman–Monteith approach[14], other responses such as increasing leaf area index are generally omitted in drought projections, with few exceptions (e.g. Liu *et al* 2023). Finally, the effects of rising CO_2 on crop yields remain uncertain, not only in terms of total production (McGrath and Lobell 2013) but also regarding physiological processes that influence crop nutritional quality (Toreti *et al* 2020). Overall, the uncertainties discussed above—ranging from methodological choices in AED estimation to vegetation-type variability and structural model assumptions—highlight both the complexity of representing vegetation–CO_2 interactions and the need for further research.

5. Conclusions

Despite clear evidence from ecophysiological studies, our meta-analysis reveals that the vegetation response to CO_2 remains largely absent from most drought projections. Neglecting plant physiology leads to a systematic overestimation of future drought extent by 17.4% under high-emissions scenarios. The overestimation is more compelling in dryland regions where policy decisions on water allocation and agricultural planning are highly sensitive to such projections. As climate adaptation and risk planning increasingly rely on drought projections, our findings highlight a critical gap in current modelling practices. In particular, the widespread reliance on offline estimations of AED—without accounting for CO_2-induced stomatal regulation—may misguide both research and policy on future water planning and management. More importantly, this methodological gap could cast doubt on climate change implications—including drought increases in many regions of the world. Regarding existing drought projections, we recommend caution in their use if they neglect vegetation response to CO_2 especially in dry climates, while we call for using at least the approaches proposed by Milly and Dunne (2016) and Yang *et al* (2019) as baseline to develop such studies in the future. Directly exporting AED values from ESM should be considered in CMIP7 since it would be a great step towards enhanced consistency between these model outputs and offline drought projections. More broadly, we endorse further interdisciplinary collaboration between plant ecophysiologists and ecohydrologists to better understand and represent CO_2-vegetation feedback (Cocozza and Penna 2022, Wilkening *et al* 2024). By avoiding the neglect of vegetation response to CO_2, the scientific community will be able to provide actionable, accurate information needed for climate-resilient water and land management in a warming world.

[14] Which are the most common methods to simulate vegetation response (e.g. Yang *et al* 2019).

Data availability statement

The data that supports the findings of this study are openly available in the supplementary files of this article.

Additional tables and results available at https://doi.org/10.1088/2752-5295/ae583c/data1.

Systematic review outputs available at https://doi.org/10.1088/2752-5295/ae583c/data1.

Meta-analysis outputs available at https://doi.org/10.1088/2752-5295/ae583c/data1.

Conflict of interest

The authors declare that there is no conflicts of interest.

CRediT author statement

Conceptualization: L V. Methodology: L V, L P, G C, D P, F J, B V S, N G, E L, E A Y. Investigation: L V, L P, E A Y, B V S, N G, I B, E L, A B, M F A, M B. Validation: L V, N G. Data curation: L V. Writing original draft: LV with significant contribution of L P, G C, D P, B V S, A B, M D. Writing—Review and editing: all the authors. Visualization: L V, L P, E L. Supervision: E B, A V G, D P.

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