Received: 12 February 2021 | Revised: 6 June 2021 | Accepted: 15 July 2021 | Published on: 4 August 2021

DOI: 10.1002/joc.7302

RESEARCH ARTICLE

International Journal of Climatology | RMetS

Global exposure of population and land-use to meteorological droughts under different warming levels and SSPs: A CORDEX-based study

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Abstract

Global warming is likely to cause a progressive drought increase in some regions, but how population and natural resources will be affected is still underexplored. This study focuses on global population, forests, croplands and pastures exposure to meteorological drought hazard in the 21st century, expressed as frequency and severity of drought events. As input, we use a large ensemble of climate simulations from the Coordinated Regional Climate Downscaling Experiment (CORDEX), population projections from the NASA-SEDAC dataset and land-use projections from the Land-Use Harmonization 2 project for 1981–2100. The exposure to drought hazard is presented for five Shared Socioeconomic Pathways (SSP1-SSP5) at four Global Warming Levels (GWLs: 1.5°C to 4°C). Results show that considering only Standardized Precipitation Index (SPI; based on precipitation), the SSP3 at GWL4 projects the largest fraction of the global population (14%) to experience an increase in drought frequency and severity (versus 1981–2010), with this value increasing to 60% if temperature is considered (indirectly included in the Standardized Precipitation-Evapotranspiration Index, SPEI). With SPEI, considering the highest GWL for each SSP, 8 (for SSP2, SSP4, SSP5) and 11 (SSP3) billion people, that is, more than 90%, will be affected by at least one unprecedented drought. For SSP5 at GWL4, approximately 2×10^6 km^2 of forests and croplands (respectively, 6% and 11%) and 1.5×10^6 km^2 of pastures (19%) will be exposed to increased drought frequency and severity according to SPI, but for SPEI this extent will rise to 17×10^6 km^2 of forests (49%), 6×10^6 km^2 of pastures (78%) and 12×10^6 km^2 of croplands (67%), being mid-latitudes the most affected. The projected likely increase of drought frequency and severity significantly increases population and land-use exposure to drought, even at low GWLs, thus extensive mitigation and adaptation efforts are needed to avoid the most severe impacts of climate change.

KEYWORDS

climate projections, CORDEX, drought, global warming levels, land-use, population, socioeconomic scenarios

1 | INTRODUCTION

Meteorological drought events are usually associated with prolonged deficits of precipitation, high temperatures, dry winds and low humidity (Mishra and Singh, 2010). Compared with other natural hazards as floods or windstorms, droughts are slowly developing and more complex events (Wilhite, 2000) and, because it is not possible to define them in a unique way (Lloyd-Hughes, 2014), multivariate perspective (Hao and Singh, 2015), advanced modelling (Mishra and Singh, 2011) and specific indicators (Heim Jr, 2002; Zargar *et al*., 2011) are required to characterize and study them. Mega-droughts such as the California drought in 2012–2014 (Griffin and Anchukaitis, 2014), the Millennium Drought in Australia (Van Dijk *et al*., 2013), the multiyear drought in South Africa in 2015–2017 (Otto *et al*., 2018), the decennial droughts in South America (Chile: Garreaud *et al*., 2020; Brazil: Cunha *et al*., 2019; Marengo *et al*., 2021) and other recent drought-related disasters (Below *et al*., 2007; Cook *et al*., 2016), also show that quantifying drought impacts can be challenging (Blauhut *et al*., 2015).

Despite such difficulties, in the last decades the scientific community made significant efforts to investigate drought risk at global (Carrao *et al*., 2016; Carrão *et al*., 2018; Meza *et al*., 2020) and country scales (Wilhite *et al*., 2014; Kim *et al*., 2015); such risk is projected to progressively increase in many regions in the 21st century (Cook *et al*., 2015, 2020) due to global warming (Pachauri *et al*., 2014). An increasing probability of severe or extreme droughts requires adequate mitigation and adaptation policies to prevent and limit their impacts and recover from their consequences (Vogt and Somma, 2000; Wilhite *et al*., 2007; Taylor *et al*., 2013; Schwalm *et al*., 2017), and to optimize the costs of interventions (Logar and van den Bergh, 2013), especially in regions of acknowledged severe risk (e.g., the Mediterranean region, Iglesias *et al*., 2007).

According to the Intergovernmental Panel on Climate Change (IPCC), in a climate change context, risk is characterized by three components: hazard, exposure and vulnerability (Cardona *et al*., 2012). Specifically, drought risk can be defined as the likelihood to incur in damages and economic losses during and after a drought (Vogt *et al*., 2018). This study focuses on the first two components, hazard (probability and severity of occurrence of a drought event) and exposure (exposed assets and population to drought hazard), leaving vulnerability (sensitivity of the exposed assets and population to cope with damaging effects of drought hazard) for following studies.

Drought hazard is by far the most studied component, and many works have investigated past and future drought trends. At global scale, especially in recent decades, observed drought frequency and severity showed small increase (Seneviratne, 2012; Sheffield *et al*., 2012; Spinoni *et al*., 2019), which is more pronounced if temperature is taken into account in the drought index formulation (Trenberth *et al*., 2014) instead of considering only precipitation (Spinoni *et al*., 2014). When including the increase of the evaporative demand, a few hotspots emerge, including southern South America, the Mediterranean region and southern Africa (Greve *et al*., 2014).

On the other hand, drought hazard projections show a high degree of complexity, also because of inherent uncertainties in climate models, especially for precipitation and over some regions of the world (Ficklin *et al*., 2016; Dosio *et al*., 2019). This could lead to uncertain drought projections (Dai and Zhao, 2017; Zhao and Dai, 2017), an issue affecting different generations of models (Burke and Brown, 2008; Orlowsky and Seneviratne, 2013). Being aware that such uncertainties cannot be totally neglected, some studies reported that future drought hazard is likely to increase more steeply in the future than in the recent past, especially under the most severe emission scenarios (Cook *et al*., 2014; Zhao and Dai, 2015). The role of temperature in future droughts is more pivotal than for the past (Ahmadalipour *et al*., 2017), especially over regions where future drought tendencies are spatially inhomogeneous, for example, Europe (Spinoni *et al*., 2018) and the United States (Jeong *et al*., 2014).

Global projections of meteorological droughts are commonly based on Global Climate Models (GCMs), whose low spatial resolution limits their ability to simulate local processes (Cook *et al*., 2014) in regions of complex topography and heterogeneous land-use (Xu *et al*., 2019a). Recently, Spinoni *et al*. (2020) published the first study on drought projections at global scale based on Regional Climate Models (RCMs) from the Coordinated Regional-climate Downscaling Experiment (CORDEX; Giorgi and Gutowski Jr, 2015). This study was the first to apply CORDEX data at global scale, although RCMs have already been used for drought studies at continental (e.g., Europe: Spinoni *et al*., 2018), macroregional (e.g., Middle-East and North Africa: Driouech *et al*., 2020; West Africa: Diasso and Abiodun, 2017; South Asia: Samantaray *et al*., 2021) and country scales (e.g., South Korea: Nam *et al*., 2015).

At the 21st Conference of the Parties in Paris (COP21; UNFCCC, 2015), signatory countries agreed to keep global warming below 2°C above pre-industrial levels, with the aim of limiting it to 1.5°C (Hare *et al*., 2016). Since then, studies assessing the impact of climate change under specific Global Warming Levels (GWLs) are becoming increasingly common (IPCC, 2018). In this study, we compute drought projections at specific GWLs (from 1.5°C to 4°C). Compared with previous works, the combined use of GCMs and RCMs at global scale (for a total of around 150 simulations), the spatial resolution (0.44°), and the critical investigation of the key role of temperature make this study a significant step forward.

Compared with drought hazard, the number of scientific publications investigating exposure to drought is smaller, but local studies focusing on the exposure of population or single land-use categories are not rare; examples include impacts on mental (O'Brien *et al*., 2014) and physical health (Ebi and Bowen, 2016), poverty (Winsemius *et al*., 2015), children undernutrition (Hirvonen *et al*., 2020), social issues (Wilhite and Buchanan-Smith, 2005; Below *et al*., 2007), forest ecosystems (Grossiord *et al*., 2014; Anderson *et al*., 2018), pastures (Rolo and Moreno, 2019) or croplands (Peduzzi *et al*., 2009). Such studies often focus on developing countries as sub-Saharan regions (Gray and Mueller, 2012; Kamali *et al*., 2018), but there are also a few related to other countries as, for example, Australia (Kiem *et al*., 2016), China (Zhang *et al*., 2011) and South Korea (Kim *et al*., 2015). The effects of recurrent severe droughts on population are known to be highly impacting in least developed countries (Miyan, 2015; Marengo *et al*., 2017), affecting especially early child health (Kumar *et al*., 2016), and possibly forcing poverty and migration (Sheffield and Wood, 2011), and such effects could increase in a warming world (Liu *et al*., 2018; Gu *et al*., 2020).

Forests are known to be vulnerable to climate change and drought (Choat *et al*., 2012; Hlásny *et al*., 2014) and in general to natural hazards (Seidl *et al*., 2017; McDowell *et al*., 2020) that could lead to increased tree mortality due to a decreased ability to survive insect outbreaks (Kurz *et al*., 2008) or forest fires (Boer *et al*., 2020) in case of, for example, combination with extreme heat-waves (Rennenberg *et al*., 2006) or devastating events such as the California droughts in 2012–2015 (Asner *et al*., 2016). Also pastures are known to be affected by climate change (Tubiello *et al*., 2007; Cullen *et al*., 2009; Perera *et al*., 2019), and in particular droughts (Ding *et al*., 2011), which can even be a contributory cause of land abandonment (Doblas-Miranda *et al*., 2017), and whose effects are likely to increase in coming decades (Soussana *et al*., 2010). Similar impacts are expected in agricultural production (Gornall *et al*., 2010; Schwalm *et al*., 2012; Swain and Hayhoe, 2015; Cook *et al*., 2018), which could suffer from serious yield reductions and decreased crop productions (Lesk *et al*., 2016; Zampieri *et al*., 2017; Toreti *et al*., 2019) during and following severe events like the droughts in the 2010's in Russia (Wegren, 2011), China (Zhang *et al*., 2012), and California (Howitt *et al*., 2014; Medellín-Azuara *et al*., 2016).

This study aims at improving our understanding of future exposure to droughts of population and natural ecosystems at different GWLs under several shared socioeconomic pathways (SSPs; O'Neill *et al*., 2014, 2017). The regions projected to face more frequent and severe droughts, sometimes aggravated by socioenvironmental factors (Kallis, 2008; Seager *et al*., 2015; Williams *et al*., 2015; Haile *et al*., 2020), are likely to see a consequential increase in drought risk (Cook *et al*., 2015), sometimes leading to irreversible land degradation and desertification (Reed and Stringer, 2016). Therefore, global drought projections could help implementing mitigation (Taylor *et al*., 2013) and adaptation policies (Logar and van den Bergh, 2013), and provide the basis for future studies incorporating the vulnerability component of drought risk in such projections.

This article is structured as follows: Section 2 (Data and Methods) describes input climate and land-use data, drought indicators and derived parameters, and details on climate and socio-economic scenarios; Section 3 (Results and Discussion) presents drought hazard and exposure projections at continental and macroregional scales, with special focus on the role of temperature for droughts and on the SSP5 scenario (fossil-fueled development; Kriegler *et al*., 2017); Section 4 (Conclusions) sums up the main findings and anticipates the next steps.

2 | DATA AND METHODS

2.1 | Climate data

In this study, drought indicators and derived parameters are computed from monthly precipitation (P), minimum (T_N) and maximum temperature (T_X) data from the CORDEX datasets for the period 1981–2100. For each of the 14 CORDEX domains (see: www.cordex.org), we obtain all possible combinations of GCMs and RCMs simulations providing both precipitation and temperature data for the moderate Representative Concentration Pathway RCP4.5 (Thomson *et al*., 2011) and extreme RCP8.5 (Riahi *et al*., 2011). We excluded the RCP2.6 and the RCP6.0 (Van Vuuren *et al*., 2011a, 2011b), because of their unavailability for most CORDEX domains.

Though CORDEX simulations have been rarely applied at global scale (Spinoni *et al*., 2020), multidomain approaches have been used for different regions, for example, by Zittis *et al*. (2019) and Legasa *et al*. (2020) over Europe and Africa. CORDEX simulations over individual domains have been thoroughly evaluated with respect to not only mean climatology, but also extreme events and physical processes. Here, only few representative examples for each domain are listed: North America (Martynov *et al*., 2013), Central America (Cavazos *et al*., 2020), South America (Solman and Blázquez, 2019; Llopart *et al*., 2020), Europe (Jacob *et al*., 2014), Africa

(Nikulin *et al.*, 2012; Careto *et al.*, 2018); Central Asia (Ozturk *et al.*, 2012), East Asia (Um *et al.*, 2017), South Asia (Sanjay *et al.*, 2017), Australasia (Evans *et al.*, 2021), Arctic (Koenigk *et al.*, 2015) and Antarctica (Souverijns *et al.*, 2019), as well as the newest sub-domains Mediterranean (Ruti *et al.*, 2016; Dell'Aquila *et al.*, 2018), Middle East North Africa (Ozturk *et al.*, 2018) and South-East Asia (Supari *et al.*, 2020; Tangang *et al.*, 2020).

To ensure spatial homogeneity, we select simulations at comparable spatial resolution (~0.44°), thus excluding higher resolution subsets over single domains as the EURO-CORDEX (0.11°; Jacob *et al.*, 2014) and the new simulations from CORDEX-CORE at 0.22° (Gutowski *et al.*, 2016; Giorgi *et al.*, 2017). The full list of simulations includes 23 CMIP5 GCMs combined with 33 RCMs (Table 1), which leads to a heterogeneous number of GCM-RCM combinations at global scale, from a minimum of 16 over Antarctica to a maximum of 145 over the Middle-East, counting both RCPs (Figure S1). Compared with Spinoni *et al.* (2020), the number of simulations increases by around 40%. We use only the simulations with no reported outliers and unrealistic values, and with complete metadata. Despite the unprecedented number of simulations, the interpolation of single models over a common 0.44° grid does not produce heterogeneities at borders between CORDEX domains: in fact no border shows precipitation and mean temperature discontinuities – averaged over 1981–2010 – larger than 5% and 1°C, respectively (excluding the Urals for temperature).

Observed precipitation and temperature data for validation include the latest version of the Deutscher Wetterdienst's Global Precipitation Climatology Centre (GPCC version 8; Schneider *et al.*, 2018) and the University of East Anglia's Climate Research Unit (CRU TS version 4.04; Harris *et al.*, 2020) datasets.

As explained, in this study we focus on the GWLs, following the methodology of Dosio and Fischer (2018) (see also Vautard *et al.*, 2014; Kjellström *et al.*, 2018). In particular, we firstly define 1981–2010 as reference period and we derive the corresponding observed global (land and oceans) temperature increase compared with the pre-industrial values (1881–1910 in this study; Hawkins *et al.*, 2017), which is 0.96°C according to NASA Goddard's Global Surface Temperature Analysis dataset (GISTEMPv4; Hansen *et al.*, 2010). Secondly, for each GCM run (and either RCP), we look for the first year (obtained from running mean values) corresponding to an additional global mean warming by 0.54°C (1.04°C, 2.04°C and 3.04°C) compared with the reference period. Thus, the 30-year period centred on that year corresponds to a GWL of 1.5°C (2°C, 3°C and 4°C) for that run. With this approach, where the GWLs are defined by using GCMs and therefore applied to RCMs (see Dosio *et al.*, 2018), the climate and drought quantities are calculated for 30-year periods corresponding to GWLs: for most GCM runs, RCP8.5 allows reaching all GWLs considered in this study, while RCP4.5 allows reaching 1.5°C and 2°C only.

2.2 | Drought hazard indicators and derived parameters

All calculations from input variables to drought indicators and parameters are performed at every grid point for each individual simulation (and RCPs) and the resulting indicator is re-gridded over a common 0.44° global grid. The output drought-related quantity eventually represents the ensemble median of the corresponding variable.

Thus, for a given model, scenario and grid point, we use precipitation data to obtain the standardized precipitation index (SPI, McKee *et al.*, 1993), and precipitation and temperature data to obtain the standardized precipitation-evapotranspiration index (SPEI; Vicente-Serrano *et al.*, 2010; Begueria et al., 2014). The two indicators, both computed at 12-month scale (SPI-12 and SPEI-12) to avoid excessive variability typical of shorter accumulation periods (Cook *et al.*, 2014), are computed using the entire period 1981–2100 as baseline, as done in Spinoni *et al.* (2020). The SPEI-12 is based on the difference between precipitation and potential evapotranspiration (PET), which in this study is calculated using the Hargreaves–Samani equation (Hargreaves and Samani, 1985), which indirectly allows including the role of temperature in meteorological drought projections.

PET estimates the evaporative demand (E_0), which depends on net radiation, vapour pressure, air temperature and wind speed (Donohue *et al.*, 2010). Although PET is usually calculated by means of the Penman–Monteith's approach (Allen *et al.*, 2006; Sheffield *et al.*, 2012; Trenberth *et al.*, 2014), such method is not free from criticism due to specific thresholds and unlimited supply of moisture, that is not realistic in very dry conditions (Brutsaert and Parlange, 1998). When such meteorological variables are not available, the alternative option is to apply methods based on temperature and precipitation only; to this regard, the Hargreaves–Samani formulation is considered the one performing best (Shahidian *et al.*, 2012; Fisher and Pringle III, 2013), although it tends to overestimate evaporation in hot-humid conditions and underestimate it in windy regions (Tabari, 2010; Tabari *et al.*, 2013). Such uncertainties in PET are eventually reflected in the SPEI, thus the use of formulations based only on temperature to obtain PET in a warming atmosphere might lead to exaggerated future droughts (Milly and Dunne, 2016; Dewes *et al.*, 2017; Teuling, 2018).

TABLE 1 List of simulations used in this study

GCM	RCM				
CCCma-CanESM2	CCCma-CanRCM4	IITM-RegCM4-4	SMHI-RCA4	UQAM-CRCM5	
CMCC-CM	CMCC-CCLM4-8-19				
CNRM-CERFACS-CNRM-CM5	HMS-ALADIN52	CLMcom-CCLM4-8-17	CLMcom-CCLM-5-0-2	CLMcom-CCLM5-0-6	CNRM-ALADIN52
	CNRM-ALADIN53	CSIRO-CCAM	IITM-RegCM4-4	RMIB-Ugent-ALARO-0	SMHI-RCA4
CSIRO-BOM-ACCESS1-0	CSIRO-CCAM				
CSIRO-BOM-ACCESS3-0	CSIRO-CCAM				
CSIRO-QCCCE-MK3-6-0	CSIRO-CCAM	IITM-RegCM4-4	SMHI-RCA4		
ICHEC-EC-EARTH	CLMcom-CCLM4-8-17				
	CLMcom-CCLM4-8-17-CLM3-5	CLMcom-CCLM-5-0-2	CLMcom-CCLM5-0-6	DMI-HIRHAM5	KNMI-RACMO21P
	KNMI-RACMO22E	KNMI-RACMO22T	MPI-CSC-REMO2009	SMHI-RCA4	SMHI-RCA4-SN
	UniLund-RCA4-GUESS				
IPSL-IPSL-CM5A-LR	IITM-RegCM4-4	GERICS-REMO2009			
IPSL-IPSL-CM5A-MR	IPSL-INERIS-WRF331F	LMD-LMDZ4NEMOMED8	SMHI-RCA4		
MIROC-MIROC5	CLMcom-CCLM5-0-6	CSIRO-CCAM	GERICS-REMO2009	SMHI-RCA4	
MOHC-HadGEM2-ES	BOUN-RegCM4-3.5	CLMcom-CCLM4-8-17	CLMcom-CCLM-5-0-2	CLMcom-CCLM5-0-6	CSIRO-CCAM
	GERICS-REMO2009	ICTP-RegCM4-3	KNMI-RACMO21P	KNMI-RACMO22E	KNMI-RACMO22T
	NCAR-AZ-WRF	NCAR-RegCM4	SMHI-RCA4		
MOHC-HadGEM2-AO	MOHC-HadGEM3-RA				
MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17	CLMcom-CCLM4-8-17-CLM3-5	CLMcom-CCLM-5-0-2	CLMcom-CCLM5-0-6	CSIRO-CCAM
	GUF-CCLM-4-8-18	ICTP-RegCM4-3	MGO-RRCM	MPI-CSC-REMO2009	NCAR-AZ-WRF
	NCAR-RegCM4	SMHI-RCA4	SMHI-RCA-SN	UQAM-CRCM5	
MPI-M-MPI-ESM-MR	BOUN-RegCM4-3.5	ICTP-RegCM4-3	IITM-RegCM4-4	SMHI-RCA-SN	UQAM-CRCM5
NCAR-CCSM4	CSIRO-CCAM				
NCAR-CESM1	CYI-WRF351				
NCC-NorESM1-M	CSIRO-CCAM	DMI-HIRHAM5	SMHI-RCA4		
NOAA-GFDL-GFDL-CM3	CSIRO-CCAM				
NOAA-GFDL-GFDL-ESM2G	GERICS-REMO2009				
NOAA-GFDL-GFDL-ESM2M	CSIRO-CCAM	IITM-RegCM4-4	NCAR-AZ-WRF	NCAR-RegCM4	SMHI-RCA4
UQAM-GEMatm-Can	UQAM-CRCM5				
UQAM-GEMatm-MPI	UQAM-CRCM5				
UQAM-GEMatm-MPI-ESMsea	UQAM-CRCM5				

Once we obtain monthly time series of SPI-12 and SPEI-12 for 1981–2100, we adapt the theory of runs (Yevjevich, 1967) to define the occurrence of a meteorological drought event: in particular, a drought event is defined to start when SPI-12 (same holds for SPEI-12) goes below −1 for at least two consecutive months, and ends when the indicator goes above 0 for at least two consecutive months. The number of drought events in a period is called drought frequency (DF). In addition, we also calculate the average severity of drought events (DS), computed as the sum over the negative indicator values (in absolute values) during the event, and the unprecedented drought events (PK), that is, the number of events (in a given future period) more severe than the most severe drought event recorded in 1981–2010.

Thus, for each GCM-RCM run (and either RCP), we compute DF and DS for 1981–2010 and DF, DS and PK for four GWLs, namely 1.5°C, 2°C, 3°C and 4°C. Subsequently, we calculate the ensemble median of these quantities from all the GCMs-RCMs and RCPs combinations available for that grid point (following also Feyen *et al*., 2020), assuming that the different assumptions associated to the two RCPs have very limited impact on climate-based projections (note for instance that CORDEX RCMs simulations do not include vegetation dynamics or time-varying anthropogenic aerosols, see Boé *et al*., 2020). Thus, the approach used here focuses on GWLs irrespectively of how and when they will be reached, assuming that the spatial distribution of climate variables (and their variability) is the same at the same GWL, independent of the emission scenario. Such an approach has been frequently applied in recent drought-related studies (Samaniego *et al*., 2017; Marx *et al*., 2018; Samaniego *et al*., 2018) and, though the mentioned assumptions are a source of uncertainties, they are not generally affecting the main results when dealing with drought.

Several different methods exist to account for the uncertainty in climate models' projections (that can be substantial, see, e.g., Dosio *et al*., 2020) and to define the robustness of the climate change signal (see discussion in Mastrandrea *et al*., 2010 and Dosio *et al*., 2019). Here we follow the methodology applied by Spinoni *et al*. (2020) and derived from Collins *et al*. (2013): we define that the change in an index is significant in sign if two-thirds of simulations agree on the sign of change, significant in magnitude if the ensemble median change is larger than the inter-model variability over 1981–2010, robust if the change is both significant in sign and magnitude, uncertain if the change is not significant in sign nor in magnitude. Results are shown at different aggregation scales, namely: global, continental and macroregional. Macroregions are defined according to Iturbide *et al*. (2020) and are shown in Figure S2.

2.3 | Population and land-use data

To investigate future global population exposure to droughts, we use global population projections from the NASA-SEDAC datasets (Jones and O'Neill, 2016). We apply the newest available version (v1.01) at 0.125° resolution for the period 2000–2100, qualitatively and quantitatively consistent with the SSPs (Jones and O'Neill, 2020). Such projections divide between urban and rural population, but we use total population and we assume that the base year (2000) represents 1981–2010. We use data for five SSPs: green growth (SSP1; Van Vuuren *et al*., 2017), middle of the road (SSP2; Fricko *et al*., 2017), regional rivalry (SSP3; Fujimori *et al*., 2017), deepening inequality (SSP4; Calvin *et al*., 2017) and fossil-fueled development (SSP5; Kriegler *et al*., 2017). Figure S3 shows the macroregional population changes in the 21st century according to the five SSPs.

Besides population, we investigate the future exposure to drought of forests, pastures and croplands. As land-use data, we use the harmonized set of scenarios by the Land-Use Harmonization project 2 (LUH2), based on the estimation of annual fractional land-use patterns and transitions, and agricultural management information, from 850 to 2100 at 0.25° resolution (Hurtt *et al*., 2020). To ensure consistency with population projections, we use land-use data following the same SSPs.

LUH2 data can be grouped into five main classes: primary (never impacted by human activities) and secondary (recovering from human disturbance) vegetation, urban, croplands and pastures. In this study, we focus on croplands (including all five crop types: C_3 annual and perennial, C_4 annual and perennial and C_3 nitrogen-fixing), pastures (considering only managed pastures and excluding rangelands) and forests (derived from the forested fractions of both primary and secondary vegetation). LUH2 is primarily a land-use product and its focal point is the human use of land, so the distinction of vegetation into forested and non-forested areas can be seen as first-order land cover classification not free from uncertainties (see https://luh.umd.edu/faq.shtml for details). In Appendix S1, we show the land-use changes from 1981–2010 to 2100 (Figure S4).

2.4 | Exposure to drought: combining climate and socioeconomic scenarios

In order to assess the exposure of population and assets to drought hazard under different combinations of climatic and socioeconomic conditions, it is necessary to determine the compatibility between GWLs and SSPs (Rogelj *et al*., 2012; Pachauri *et al*., 2014; Van Vuuren and Carter, 2014; O'Neill *et al*., 2016). Table S1 summarizes the viable combinations: SSP1 is compatible with GWL of 1.5°C, SSP2 up to 2°C, SSP4 up to 3°C and both SSP3 and SSP5 up to a 4°C warming.

Each of the SSPs is provided with parent global temperature projections for the 21st century (Riahi *et al*., 2017; see also: https://tntcat.iiasa.ac.at/SspDb/). To each SSP, we assign the year corresponding to the GWL effectively reached under its development trajectory. Therefore, for each SSP, we select population values corresponding to the year representing the GWL (which therefore represents the average of a 10-year window, see Table S2) while for land-use classes we use the average values of a 10-year window centred over the year representing the GWL.

Here we estimate the projected population and land-use exposure to an increase in DF and DS of drought events, but we highlight that estimates of exposure do not incorporate vulnerability components. Moreover, we refer to total population, therefore an increase in the hazard in the grid cell corresponding to a mega-city results in a much larger increase in percentage of exposed population compared with an increase in hazard in sparsely inhabited areas. For land-use, we focus at fractions of the grid covered by each class and consequently their total extent exposed, with no focus at its productivity (Keeling and Phillips, 2007; Knox *et al*., 2012), because no global high-resolution productivity projections of forests, croplands and pastures under multiple SSPs are available yet.

Ideally, global projections of drought hazard and exposure of population and land-use to such hazard should be complemented with the vulnerability component in order to map the drought risk in the 21st century. The estimation of vulnerability to droughts is challenging because can depend on dynamic social, environmental (e.g., land-use and water resources), economic, health, energy, infrastructural and other factors and consequently requires multidimensional models (Naumann *et al*., 2014; Zarafshani *et al*., 2016). Combining future drought hazard, exposure and vulnerability is left for future studies.

3 | RESULTS AND DISCUSSION

3.1 | Drought hazard projections

Before investigating future drought hazard and in order to exclude systematic biases, we compared DF and DS over 1981–2010 derived from observed data (GPCC and CRU) with the results from the CORDEX ensemble (for this specific comparison modelled SPI and SPEI are computed using 1981–2010 as baseline).

The overall agreement between simulations and observations is satisfactory and no systematic biases are found, apart from a slight underestimation of DS by the simulations at tropical latitudes. Areas where biases in DS and DF are larger than 10% are mainly located over northwestern Amazonia and the Democratic Republic of Congo, where simulations overestimate DF and underestimate DS. Notably, these regions are known for the sparse network of rainfall gauges and temperature stations, not even all included in GPCC and CRU datasets (e.g., northwestern Amazonia, see Limberger and Silva, 2018) and, consequently, prone to observational uncertainty (Schneider *et al*., 2014; Harris *et al*., 2020). Regarding the inter-model spread of CORDEX simulations for 1981–2010, it is almost everywhere below 0.5 events/10 yr for both indicators. For drought severity the spread is larger than 20% of the ensemble median only in southern Argentina, southwestern United States, northern Kazakhstan and the Democratic Republic of Congo (Figure S5).

The first aim of this study is to assess where and to what extent meteorological droughts are likely to become more frequent and severe in a progressively warmer world. Results for DF are shown in Figure 1: if SPI is considered, most areas at mid and high latitudes in the Northern Hemisphere show a decrease in DF linked to increasing projected precipitation (Figure S6; Table S3), especially above 3°C warming. Under such warming, an increase in DF becomes robust over Mexico, southern South America, the Mediterranean region and southern Africa. On the other hand, if SPEI is considered, most of the land areas of the World – excluding high latitudes in both Hemispheres and southeastern Asia – are projected to experience an increase in DF, which becomes progressively larger with increasing GWL. In particular, the increase is robust for the Western U.S. already at GWL 1.5°C, while at 4°C warming most of the regions are projected to face an increase in DF up to more than 2 events/decade compared with 1981–2010. Differences in DF between 1.5°C and 2°C warming are larger at high latitudes for SPI (decrease) and at tropical and mid-latitudes for SPEI (increase). Results over ice caps (and hot or cold deserts) are difficult to interpret, because monthly rainfall is usually very low there, so that small variations could be misinterpreted for large deviations from normal (Charney *et al*., 1975; Pomeroy *et al*., 2007).

Not surprisingly, the projections for DS show spatial and temporal patterns like those of DF (Figure S7), but in this case the decreasing tendencies based on SPI are already robust at low GWLs over cold regions in both Hemispheres. Such regions also exhibit the largest inter-model spread, although, overall, DS shows smaller

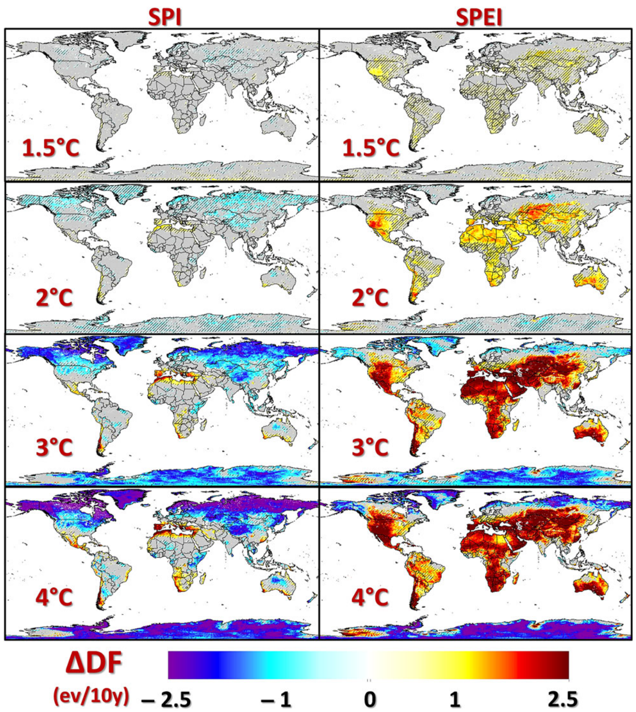

FIGURE 1 Change in drought frequency (DF) between 1981–2010 and periods corresponding to GWLs according to SPI and SPEI. Areas where change is significant in sign are represented by colour-scale values; dashed lines are superimposed if change is not significant in magnitude; grey represents areas where change is not significant in both magnitude and sign [Colour figure can be viewed at wileyonlinelibrary.com]

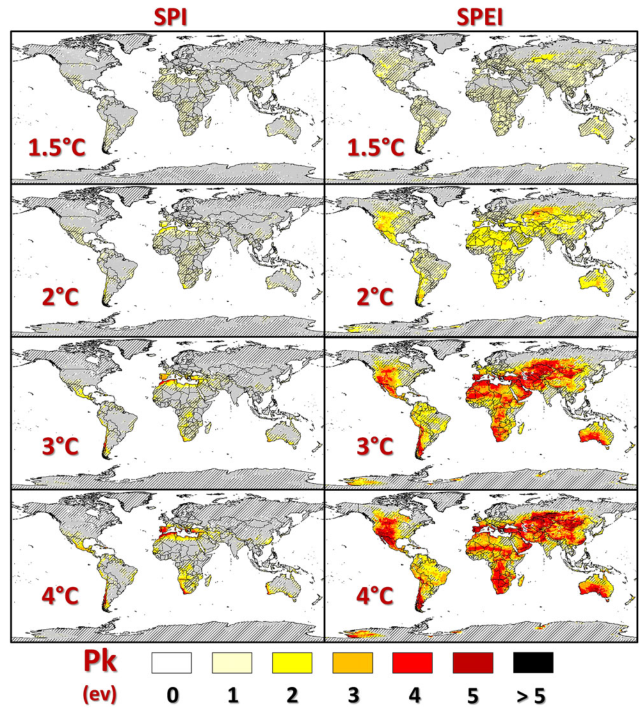

FIGURE 2 Number of events (over each 30-year period corresponding to the GWLs) more severe than the most severe one occurred in 1981–2010 (PK), according to SPI and SPEI. Grey represents areas where at least two-thirds of the simulations project 0 PK, otherwise they are represented by colour-scale values. Dashed lines are superimposed if the number of PK is projected by less than two-thirds of simulations [Colour figure can be viewed at wileyonlinelibrary.com]

inter-model variability than DF (both evaluated with the standard deviation of the ensemble), which, in turn, shows smaller values for SPI than for SPEI (Figure S8).

The second question addresses the future occurrence of unprecedented extreme droughts (PK). The patterns of PK (Figure 2) are related to those of DF (and DS): for SPI, approximately 33% of the World is likely to experience unprecedented events starting from 1.5°C warming (Figure S9); for some areas (Chile, western Mediterranean region and South Africa) the projections of unprecedented droughts (compared with 1981–2010) are robust already at GWL 2°C. Under higher GWLs, robust projections show up to 4–5 unprecedented droughts (in the 30-year period) over Chile, the Mediterranean region, southwestern South Africa and southwestern Australia. For SPEI, approximately 75% of the World is likely to experience at least one unprecedented drought at GWL 2°C or higher, and at least three of such events over 67% of the World at GWL 4°C (Figure S10). Robust projections of more than 3 unprecedented droughts are visible over the United States, Mexico, Chile, large parts of Africa, central Asia and Australia at GWLs 3°C and 4°C, with only the high latitude regions and part of South-East Asia and New Zealand not projected to face unprecedented droughts. Macroregional statistics for DF, DS and PK are reported in Tables S4 and S5.

The drought hazard projections discussed here generally agree with those reported by Zhao and Dai (2017), Spinoni *et al.* (2020) and Ukkola *et al.* (2020), but the larger number of simulations enables higher detail on transition areas such as Amazonia, Central Europe and the Sahel. The most relevant exception refers to south-eastern Asia, where – according to seasonal rainfall projections discussed in Tangang *et al.* (2020) and Supari *et al.* (2020) – Indonesia is projected to face drying tendency in summer and autumn. Contrary to previous studies, which generally focused on long-time horizons (such as the end of the 21st century), our study shows that DF and DS can significantly increase even at low GWLs. This is of crucial importance in highly productive regions such as China, where overall losses due to droughts can substantially increase even from GWL 1.5°C to GWL 2°C (Su *et al.*, 2018).

Combining the results of single drought variables, Figure 3 shows areas likely to be subjected to more frequent, severe and/or unprecedented events at different

GWLs. We assigned a score to the increase of each quantity (DF, DS and PK) for each single indicator (SPI and SPEI): 0 if there is no increase, 1 if there is a significant increase in sign and 2 if the increase is robust. Therefore, the score ranges from 0 (no increase for any category and indicator) to 12 (robust increase for all categories and indicators). Already at GWL 1.5°C, most land areas are likely to experience an increase in at least one drought quantity. At higher GWLs, drought hotspots (regions with the highest total score) become evident over Central America, Chile and southern Argentina, the Mediterranean region, the Atlantic region of Western Africa and southern Africa, southwestern China and the western and southern coastal areas of Australia.

Figure S11 shows at which GWL some areas are projected to experience an increase – compared with 1981–2010 – in DF, DS and PK for both SPI and SPEI (thus, not necessarily linked to the inclusion of temperature in the index). This is likely to occur at GWL 1.5°C for the western Mediterranean and southwestern Africa, while for Yucatan (Mexico), eastern Brazil, Zambia, Zimbabwe and parts of southwestern China it is likely to occur only if 4°C warming is reached. At macroregional scale (Table 2), no region is likely to face an increase in DF, DS and PK for both SPI and SPEI over more than 50% of its territories at GWL 1.5°C, but such threshold is reached by southwestern South America and the Mediterranean region at GWL 2°C and by Central America, the Caribbean Islands and southwestern Africa at GWL 4°C. Over cold and very cold regions, less than 1% of grid points are likely to see a combined increase in DF, DS and PK, for both the SPI and SPEI under any GWL.

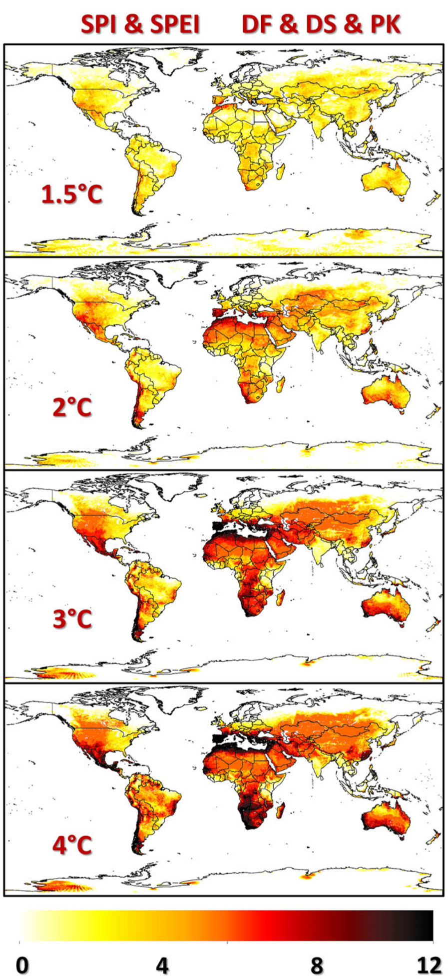

FIGURE 3 Spatial distribution of overall drought hazard score at different GWLs by combination of drought indicators (SPI-12 and SPEI-12) and the drought hazard quantities used in this study (drought frequency, severity and number of unprecedented events) [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | Future population exposure to droughts

When estimating the impacts on population and land-use, several combinations of SSPs, GWLs, drought indicators and derived hazard quantities are possible: therefore, we first focus on the highest GWL compatible with each SSP, whereas other possible combinations are discussed later. Figure 4 shows the total population at continental and global scales exposed to an increase in both DF and DS (compared with 1981–2010) under the four GWLs. Generally, for every combination of GWL and SSP, the use of SPEI results in larger values of exposed population than when using SPI: for instance, the increase in exposed population goes from around 150 million at 1.5°C warming to 350 million at 2°C warming when using SPI, but from 2 billion to nearly 4 billion with SPEI. These results are similar with all compatible SSPs.

At high GWLs, however, the choice of SSP plays a more important role. SSP3 (regional rivalry) leads to the largest values of exposed population for Central and Southern America, Africa (comparable to SSP4) and Asia, while SSP5 (fossil-fueled development) leads to the largest values in North America, Europe (comparable to SSP3) and Oceania.

With SSP1 (green growth) less than 5% (25%) of population-in all continents-is projected to be exposed to a significant increase in DF and DS according to SPI (SPEI) (Figure S12; Tables S6 and S7). Such values increase to more than 50% of the population in Central America, Europe and Oceania under 2°C warming with SSP2 (middle of the road scenario) and when considering SPEI. With SSP4 (deepening inequality), at 3°C warming, population shows non negligible values also for SPI and, for SPEI, more than half of the population worldwide (excluding Asia) is likely to be exposed to a significant increase of DF and DS in all continents.

TABLE 2 Areas (%) projected to see a significant increase in DF, DS and PK according to both SPI and SPEI from 1981–2010 to four GWLs

Region	GWL1.5	GWL2	GWL3	GWL4
ALA	0.0	0.0	0.0	0.0
NEC	0.0	0.0	0.0	0.0
GIC	0.0	0.0	0.3	0.3
NWN	0.0	0.0	0.0	0.0
SWN	0.1	0.2	0.0	11.9
CNA	0.2	0.3	0.0	2.9
ENA	0.0	0.0	0.0	0.1
CAM	0.6	4.7	34.7	65.3
CAR	0.0	10.6	43.0	68.5
NWS	0.1	2.9	7.1	13.8
SAM	0.1	0.0	0.2	1.3
SSA	0.6	10.1	28.0	43.6
SWS	20.4	69.3	75.7	77.7
SES	0.1	1.9	3.5	5.0
AMZ	0.0	0.0	0.2	3.2
NEB	0.4	1.1	1.4	10.2
NEU	0.0	0.0	0.0	0.0
CEU	0.0	0.0	1.1	2.2
MED	14.3	53.5	85.9	91.5
SAH	0.5	5.9	15.3	18.4
WAF	0.1	1.1	4.9	7.8
NEAF	0.0	0.2	0.7	0.9
CEAF	0.0	0.0	1.1	0.8
SWAF	5.2	16.9	44.1	83.1
SEAF	0.3	1.8	12.7	42.8
CAF	0.0	0.2	7.4	11.1
NEA	0.0	0.0	0.0	0.0
NWA	0.0	0.0	0.0	0.0
WAS	0.0	0.2	6.2	8.7
CAS	0.0	0.0	0.4	2.2
TIB	0.0	0.0	0.0	0.0
EAS	0.1	0.8	1.0	8.0
SAS	0.2	0.1	0.0	0.7
SEA	1.0	2.5	3.7	6.1
NAU	1.1	4.6	6.0	11.5
SAU	1.5	12.4	32.6	40.2
ANT	0.1	0.0	0.0	0.1
ARCO	0.0	0.0	0.0	0.0
WORLD	1.1	4.7	9.5	14.4

Note: See Figure S2 for localization of regions.

With severe SSPs (SSP3 and SSP5), the total population exposed could be very high also for SPI: with SSP3 at 3°C warming and SSP5 at 4°C warming, more than 1 billion people are likely to be exposed to a significant increase in DF and DS at global scale. Such values correspond to approximately 10% and 14% of the global population with SSP3 (respectively, at GWLs 3°C and 4°C) and 15% with SSP5 at 4°C warming. According to SPEI, such exposure goes above 4 billion people at GWL 3°C with SSP3 (about 55%), SSP4 (close to 60%) and SSP5 (about 53%) and, in every continent, more than 40% of population is likely to see a significant increase of DF and DS at GWL 4°C with SSP3 or SSP5, with a value of more than 7 billion people reached with SSP3 at GWL 4°C.

Projected exposure to at least one drought more severe than those observed in 1981–2010 is shown in Figure 5. Focusing at the worst case, results show that more than 11 billion people (i.e., more than 90% of global projected population) are likely to be exposed to such unprecedented events with SSP3 at GWL 4°C, mainly in Asia (close to 6 billion) and Africa (more than 3.5 billion). It is important to note that such large values (peaking with SSP3 for Central and South America, Africa and Asia, and with SSP5 for North America and Oceania) are a consequence of the expected increase in population, rather than drought hazard. In fact, in terms of fraction of total population exposed, results show (Figure S13; Tables S8 and S9) large values already at 1.5°C warming (around 40% with SPI and more than 80% with SPEI, excluding North America), with more than 90% of population exposed to the occurrence of unprecedented events with all SSPs and for most continents at 2°C warming.

3.3 | Future land-use exposure to droughts

Figure 6 shows the land-use exposure to increased DF and DS: in absolute values, forests represent the most exposed class in North and South America, and Asia, croplands in Europe and Oceania, independently of the SSP. In Africa, on the other hand, forests are the most affected class with SSP1 and SSP2, croplands with SSP3 and SSP5 and pastures with SSP4. The use of SPEI generally results in much larger exposed values, especially at high GWLs for all land-use classes considered and, for example, for forests at the global scale, the exposure with SPEI can reach values 8 times larger than with SPI. Looking at percentages (Figure S14), pastures become the most affected class at global scale with any SSP from 2°C warming and in some continents (Central and South America, Africa and Oceania) all land-use classes show exposure larger than 60% from 3°C warming.

The SSP does not play a decisive role at GWLs 1.5°C and 2°C for any land-use class (and, for forests, even at GWL 3°C) but at GWL 3°C pastures and croplands respectively show the largest values under SSP4 (with

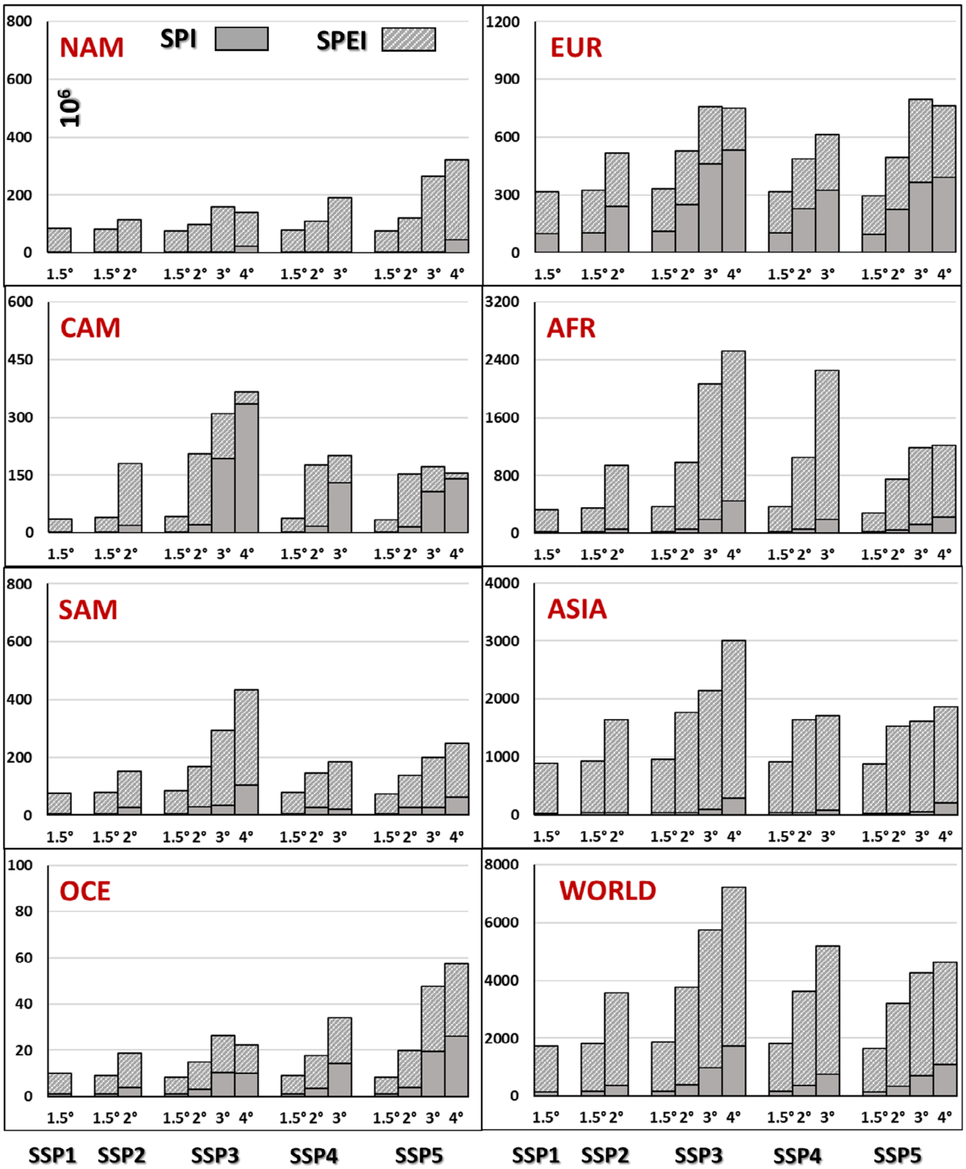

FIGURE 4 Total population (million units) exposed to significant increase of both DF and DS for five SSPs. Values are shown for both SPI (non-dashed columns) and SPEI (non-dashed plus dashed columns). Vertical scale is largely variable between the different regions due to very different population values. NAM is for North America, CAM for Central America, SAM for South America, EUR for Europe, AFR for Africa, ASIA for Asia and OCE for Oceania. See Figure S2 for details on continents and macroregions [Colour figure can be viewed at wileyonlinelibrary.com]

Africa standing out) and SSP3. At GWL 4°C, forests show the largest exposed values under SSP5, while croplands and pastures under SSP3 for both indicators.

In a World that follows a green growth (SSP1), less than 5% of examined land-use classes are projected to be exposed to a significant increase in DF and DS according to SPI, while for SPEI such values are generally below 25%, but could be close to 30% for pastures and croplands. With SSP2 (middle of the road) and at GWL 2°C, land-use shows limited exposure for SPI, but for SPEI the exposed fractions are above 50% in Central America, Europe (excluding forests), Africa and Oceania.

With a development based on deepening inequality (SSP4), the progressive increase of exposure is evident and, at 3°C warming, all categories show non negligible values also for SPI (excluding North America). With SSP4 and SPEI, more than half of pastures and croplands are projected to be exposed to a significant increase of DF and DS in all continents at GWL 3°C. With severe SSPs (SSP3 and SSP5) and according to SPEI, in every continent more than 40% of croplands are projected to experience a significant increase of DF and DS at GWL 4°C, and such fraction is even larger for pastures (>60%, excluding North America). Instead, in North America and Europe forests show exposure values below 40% even with SSP3 and SSP5, and in Asia such values are just above 40% at GWL 4°C.

The saturation effect described for population is also visible for land-use classes exposed to unprecedented droughts (Figure 7; Figure S15): with SPEI, pastures and croplands show significant exposure values larger than

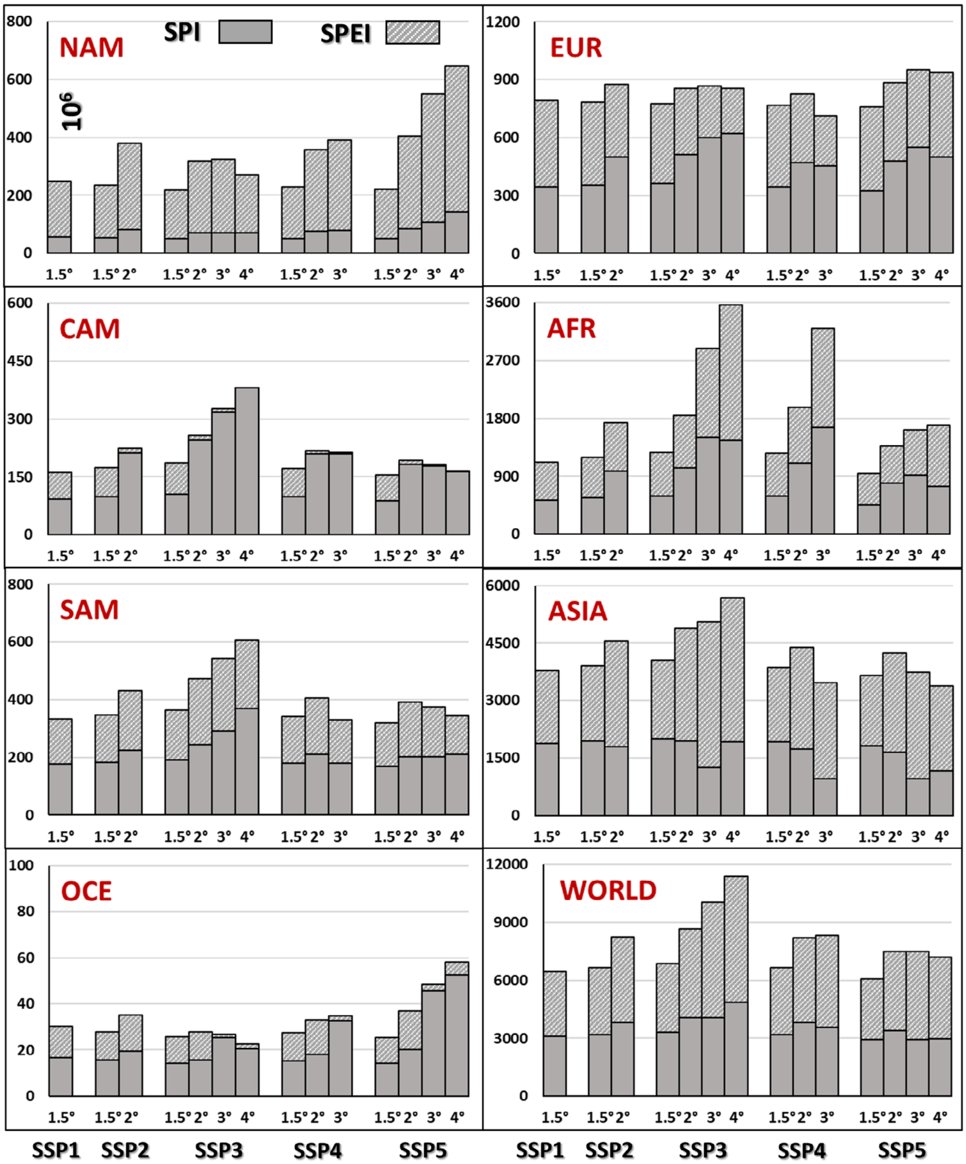

FIGURE 5 Total population (million units) significantly exposed to at least one unprecedented event for five SSPs. Values are shown for both SPI (non-dashed columns) and SPEI (non-dashed plus dashed columns) [Colour figure can be viewed at wileyonlinelibrary.com]

80% almost in every continent under all SSPs already at GWL 1.5°, and forests are below 60% of exposure only in North America and Europe, but never below 40%. With SPI, such values are smaller, but in some continents they show very large values (e.g., pastures and croplands in Central America and Oceania) and, at global scale, they are around 20% for forests (60% with SPEI), 35% for croplands (90% with SPEI) and 45% with pastures (95% with SPEI). Moving to absolute values, the saturation effect is still evident for forests (total exposure of 24–26 million km^2 with SPEI and 7–8 million km^2 with SPI) and pastures (7–10 million km^2 with SPEI and 4–6 million km^2 with SPI), while croplands show values that generally depend more on the GWL than on SSP, peaking at GWL 4°C with 19 million km^2 exposed under SSP3 (with SPEI).

3.4 | The importance of temperature in drought hazard and exposure

Although climate models consistently project a progressively warmer 21st century, precipitation projections are spatially heterogeneous, with a small global average increase, a wetting tendency over high latitudes in the Northern Hemisphere, tropical Africa and Pacific Asia and drying over Mexico, Chile, the Mediterranean Region, southwestern Africa and southern Australia (Figure S6; Table S5). Regarding drought hazard, the choice between SPI or SPEI results in differences in future DF (Figure 1), DS (Figure S7) and PK (Figure 2; Figures S9 and S10) that are almost negligible at GWL 1.5°C, start to emerge at GWL 2°C, and become progressively larger at GWLs 3°C and 4°C, due to pronounced

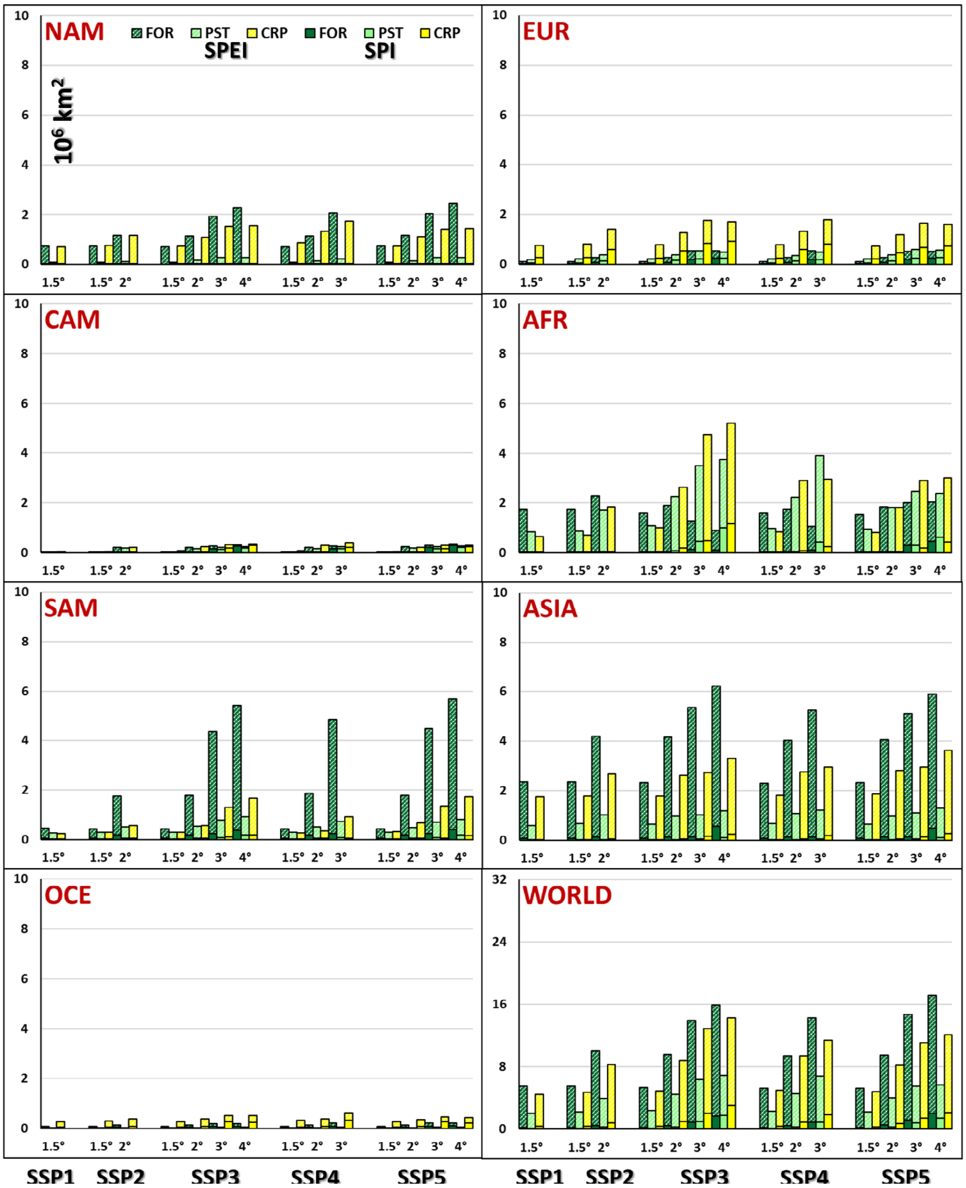

FIGURE 6 Forests (FOR), pastures (PST) and croplands (CRP), expressed in million km^2, exposed to a significant increase of both DF and DS for five SSPs. Values are shown for both SPI (non-dashed columns) and SPEI (non-dashed plus dashed columns) [Colour figure can be viewed at wileyonlinelibrary.com]

temperature increases under extreme climate scenarios in the second half of the 21st century (Pachauri *et al.*, 2014). In the Northern Hemisphere, we note regions with opposite tendencies, depending on the drought indicator, for both DF and DS (green areas in Figure 8), where a precipitation decrease is overbalanced by the temperature increase: Asia from GWL 2°C and North America from GWL 3°C. In the Southern Hemisphere, this occurs for very limited (at GWL 3°C) or limited (at GWL 4°C) areas, specifically over central western Brazil and central Argentina, central Australia. See Figures S16 and S17 and Table S8 in SM for macro-regional statistics.

Remarkable differences between the two drought indicators can therefore be found in population and land-use projected exposure to drought events. In particular, the use of temperature as a drought driver (in this case with SPEI) can be dominant over areas with unclear precipitation projections, for example, over North America, where population exposed to an increase of both DF and DS at GWL 4°C ranges between ~10% when using SPI to ~50% for SPEI (Figure S12). Population and land-use (Figure 9) show larger exposure to all drought parameters analysed in this study with SPEI than with SPI. For example, the global population exposed to a significant increase in DF is about four to five times larger with SPEI than with SPI in all SSPs (Table 3; Table S19). Larger differences are found by comparing the exposure to a significant increase in DS and slightly smaller by comparing the significant exposure to unprecedented events.

Focusing on simultaneous significant increases of DF and DS, the combination leading to the largest exposure, at global scale, is met with SSP3 at GWL 4°C (excluding forests with SSP5 at GWL 4°C) for both indicators (Figure 9).

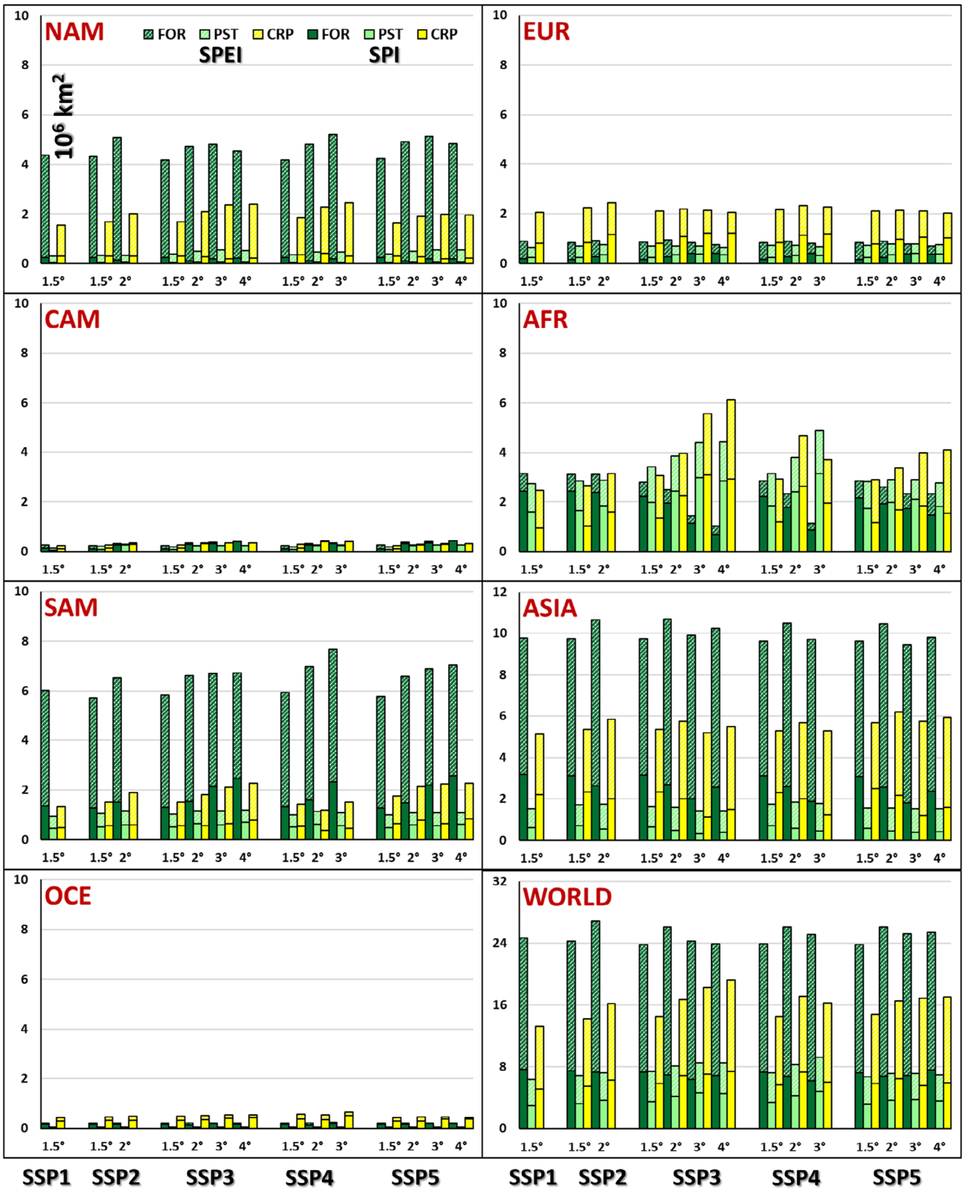

FIGURE 7 Land-use forests, pastures and croplands, expressed in million km^2, significantly exposed to at least one unprecedented event for five SSPs. Values are shown for both SPI (non-dashed columns) and SPEI (non-dashed plus dashed columns) [Colour figure can be viewed at wileyonlinelibrary.com]

However, if we focus on severe SSPs (SSP3, SSP4 and SSP5), according to SPI the exposure of each category never exceeds 20%, while with SPEI it is never below 40%. About unprecedented droughts, if we base our analyses on precipitation (SPI), the global exposure of population is ~40% for all SSPs, ~20% for forests, ~35% for croplands and ~50% for pastures; including also temperature (SPEI), such values increase to the point that at least 60% of forests and 80% of population, pastures and croplands are exposed to PK ≥1 at the highest GWL of any SSP.

Other than the clear effect of temperature, Figure 9 shows that, using SPI, population and land-use exposure to a significant increase in DS is similar – in terms of total numbers – to that related to a significant precipitation decrease, while the exposure related to significant increases in DF and PK is instead larger. This highlights the role of precipitation variability in drought projections, which can be more important than mean changes. Climate change is known to cause a higher frequency of extreme precipitation events (Giorgi *et al*., 2019) and enhanced interannual precipitation variability (e.g., Giorgi and Bi, 2005) and this likely occurs also for droughts as, due to the increased variability, regions projected to face a long-term increase in overall precipitation could face an increase in DF and experience extreme events never recorded in the past (IPCC, 2018).

Depending on drought indicators, the differences in exposure to drought tend to become larger with increasing GWL, which is expected as the SPEI includes temperature. However, this could raise questions about a possible over-estimation of drought trends by SPEI due to overestimation of PET (see Section 2.2). Thus, we also investigate population and land-use exposed to simultaneous significant increases in DF, DS and PK for both SPI and SPEI (rightmost panels in Figure 9; Table S12).

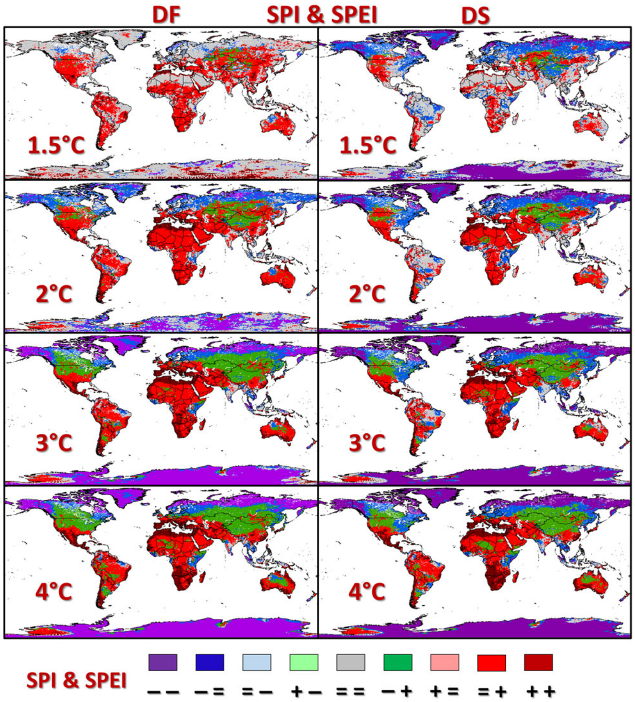

FIGURE 8 Concordance between SPI and SPEI on tendencies of drought frequency (DF) and severity (DS). Red-like areas represent significant increase for at least one indicator, blue-like significant decrease for at least one indicator, grey-like no significant change and green-like opposite tendencies [Colour figure can be viewed at wileyonlinelibrary.com]

The results show that including temperature in meteorological drought projections, without accounting for soil moisture depletion and saturation of atmospheric water vapour uptake, can indeed exaggerate some drought patterns. This occurs in particular over humid regions where a robust increase in temperature is not associated with counterpart significant drying, especially in the second half of the 21st century under more severe combinations of climate and socioeconomic scenarios. Consequently, as specific sectors potentially affected by drought could require different types of drought indicators, depending on the type of risk one wants to quantify – also depending on the specific vulnerability of such sectors to drought events – we suggest performing analyses on exposure to drought hazard by using combinations of indicators that include and neglect temperature.

3.5 | Focusing on fossil-fueled scenario (SSP5)

Because RCP8.5 allows reaching extreme warming levels (Riahi *et al.*, 2011), it can be used to analyse worst-case scenarios for drought hazard (Spinoni *et al.*, 2020). For this reason, and because SSP5 is best coupled with RCP8.5 (O'Neill *et al.*, 2016), which includes the largest number of simulations used in this study (54%), here we specifically focus on the combination SSP5-RCP8.5 (not misled with SSP5-8.5; Wyser *et al.*, 2020). The SSP5 foresees a future rapid economic growth associated with unrestricted carbon-based energy use (Van Vuuren

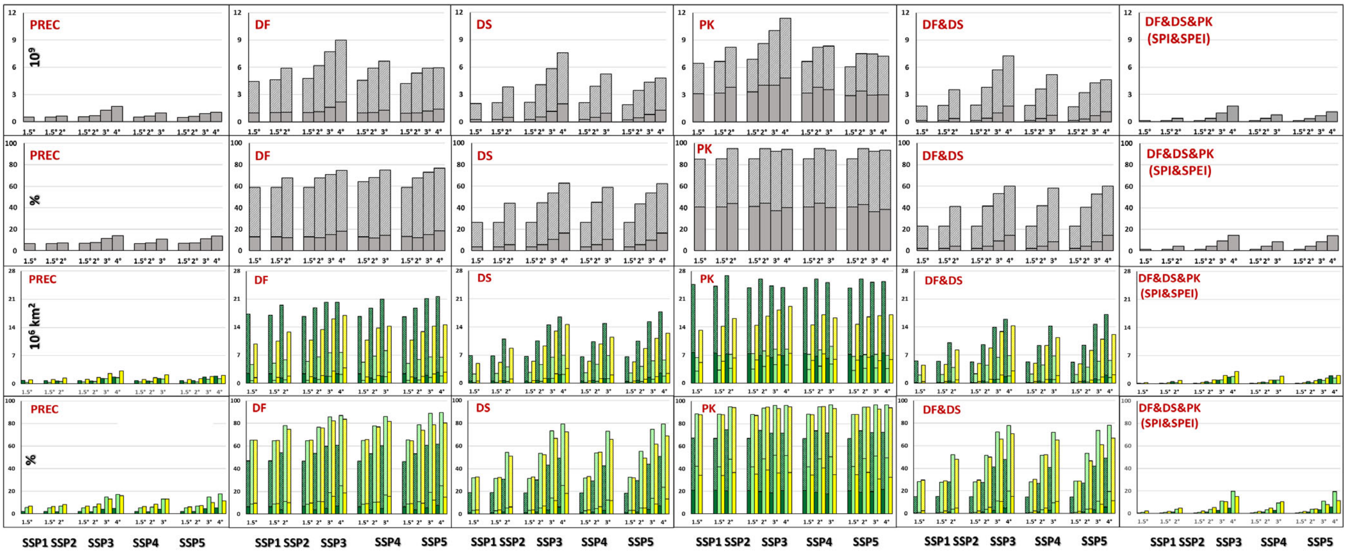

FIGURE 9 Global population (first row: billion units, second row: %) and land-use (third row: million km^2, fourth row: %) exposed to significant drying (first column) and increase of drought quantities (other columns) for viable combinations of GWLs and SSPs. Population values in grey, forested areas in dark green, pastures in light green and croplands in yellow. In columns 2 to 5, values derived using the SPI (non-dashed columns) and SPEI (non-dashed plus dashed columns) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Global population (million units) and land-use (million km^2) exposed to a significant in sign (and robust) increase in drought quantities from 1981–2010 to the highest GWL for each SSP, according to SPI and SPEI

	SSP (GWL)		SSP1	(1.5°)			SSP2	(2°)			SSP3	(4°)			SSP4	(3°)			SSP5	(4°)	
	IND/CLASS	POP	PST	CRP	FOR	POP	PST	CRP	FOR	POP	PST	CRP	FOR	POP	PST	CRP	FOR	POP	PST	CRP	FOR
SIGNIFICANT	SPI_DF (M)	989.4	0.6	1.4	2.4	1,054.7	0.8	1.8	1.4	2,183.9	2.2	3.8	2.4	1,287.9	1.6	2.8	1.7	1,421.4	1.8	2.7	2.7
	SPEI_DF (M)	4,462.2	4.7	9.8	17.2	5,873.2	5.9	12.8	19.5	9,002.6	7.7	16.9	20.2	6,674.5	8.2	14.2	21.0	5,924.9	6.5	14.6	21.6
	SPI_DS (M)	263.5	0.2	0.5	0.5	484.9	0.4	1.1	0.7	1962.5	2.2	3.7	2.1	924.4	1.2	2.1	1.2	1,256.0	1.7	2.4	2.5
	SPEI_DS (M)	2005.9	2.3	4.9	6.9	3,835.2	4.1	8.7	11.0	7,576.2	7.0	14.7	16.5	5,247.8	6.9	11.5	14.9	4,817.0	5.8	12.5	17.7
	SPI_PK (M)	3,090.4	3.0	5.2	7.7	3,802.4	3.7	6.3	7.3	4,842.4	4.6	7.4	6.9	3,564.3	4.8	6.0	6.2	2,976.4	3.6	5.9	7.6
	SPEI_PK (M)	6,464.4	6.3	13.2	24.7	8,226.9	7.2	16.2	26.9	11,374.3	8.5	19.2	23.9	8,333.9	9.2	16.3	25.1	7,217.2	7.0	17.1	25.3
	SPI_DFDS (M)	156.1	0.1	0.3	0.2	372.8	0.3	0.8	0.5	1736.1	1.8	3.1	1.7	762.5	0.9	1.8	0.9	1,093.4	1.4	2.1	2.0
	SPEI_DFDS (M)	1742.4	2.0	4.5	5.5	3,559.5	3.9	8.3	10.0	7,238.4	6.9	14.3	15.9	5,180.9	6.8	11.4	14.2	4,625.3	5.7	12.1	17.1
	ALL (M)	123.5	0.1	0.3	0.2	372.8	0.3	0.8	0.5	1735.9	1.8	3.1	1.7	762.2	0.9	1.8	0.9	1,093.3	1.4	2.1	2.0
ROBUST	SPI_DF (M)	1.5	0.0	0.0	0.0	107.1	0.1	0.3	0.2	1,593.7	1.3	2.8	1.4	675.1	0.5	1.5	0.8	997.4	1.1	1.9	1.6
	SPEI_DF (M)	137.5	0.1	0.3	0.4	2021.4	1.8	5.0	4.0	7,338.6	6.8	14.4	15.8	4,915.3	6.4	10.9	13.8	4,691.5	5.6	12.1	16.9
	SPI_DS (M)	2.3	0.0	0.0	0.0	75.5	0.1	0.2	0.0	1,286.8	1.3	2.6	1.1	342.4	0.3	1.0	0.4	776.6	1.0	1.6	1.4
	SPEI_DS (M)	59.5	0.1	0.4	0.3	1,126.4	0.9	3.0	2.3	5,966.7	5.9	12.0	12.8	3,541.2	4.6	7.8	7.1	3,722.2	4.8	9.9	13.8
	SPI_PK (M)	183.0	0.2	0.5	0.4	824.1	0.7	1.6	1.5	2,942.2	3.1	4.9	3.8	1,628.9	2.5	3.1	2.5	1856.4	2.5	3.4	4.3
	SPEI_PK (M)	2061.6	2.7	5.4	7.8	5,628.2	5.7	12.4	17.7	10,185.4	8.0	17.9	21.2	6,933.2	8.4	14.4	21.3	6,467.0	6.6	15.7	22.6
	SPI_DFDS (M)	0.0	0.0	0.0	0.0	57.5	0.0	0.2	0.0	1,083.5	0.8	2.1	0.8	302.4	0.2	0.9	0.3	662.3	0.7	1.4	1.0
	SPEI_DFDS (M)	7.4	0.0	0.0	0.0	918.8	0.6	2.5	1.3	5,632.8	5.7	11.3	11.3	3,373.1	4.3	7.5	6.5	3,482.8	4.6	9.3	12.3
	ALL (M)	0.0	0.0	0.0	0.0	57.5	0.0	0.2	0.0	1,082.5	0.8	2.1	0.8	302.4	0.2	0.9	0.3	661.8	0.7	1.4	1.0

Abbreviations: CRP, crops; DF, drought frequency; DS, drought severity; FOR, forest; PK, unprecedented droughts; POP, population; PST, pastures.

et al., 2011a; Leimbach *et al.*, 2017). It implies high mitigation challenges and relatively low challenges in adaptation: the technological progress aims at strong development at the cost of huge exploitation of fossil-fuel energy, and therefore very high CO_2 emissions (Kriegler *et al.*, 2017). With SSP5, population – subjected to massive urbanization – shall peak around the mid-2050s and subsequently decline close to current values, especially over East Asia (Samir and Lutz, 2014; Jones and O'Neill, 2016).

Results for simultaneous population and land-use exposure to increased DF, DS and PK agreed by both SPI and SPEI are shown in Figure 10. Many regions show small or negligible exposed fractions for all categories and GWLs, especially above 45°N and at tropical latitudes in Africa and Asia. Instead, regions with not negligible exposed population and land-use at GWL 2°C generally show a progressive exposure increase with increasing GWL. If we arbitrarily define as drought hotspots (under SSP5) the macroregions with at least 20% of population, pastures, forests and croplands exposed to the worst drought conditions, southwestern South America becomes hotspot at GWL 2°C, Central America, the Caribbean and the Mediterranean Region at GWL 3°C, and southwestern Africa, southeastern Africa and southern Australia at GWL 4°C.

The key role of temperature is undeniable also within SSP5: population and land-use are likely to be widely exposed to a significant increase in DF and DS (Figure 11) and to multiple unprecedented events (Figure S18) over most of the regions at GWLs 3°C and 4°C according to SPEI, while this occurs at GWL 4°C and over only few regions for SPI. Other than the extent of areas (much wider using SPEI), the effect of temperature (so the use of SPEI) allows the identification of progressive exposure over all continents (Figure 11, right panels), while for the SPI this occurs only over central America, the Mediterranean region and sparse areas elsewhere. For pastures, the most evident differences between SPI and SPEI are in sub-Saharan Africa and northeastern China. In addition, the use of SPEI shows the evolution of drought effects on boreal forests in Canada and Russia and the tropical forests of Amazonia, the Congo river basin and southern China, along with extended croplands at mid-latitudes in central US, Europe and eastern China, as well as over centreeastern

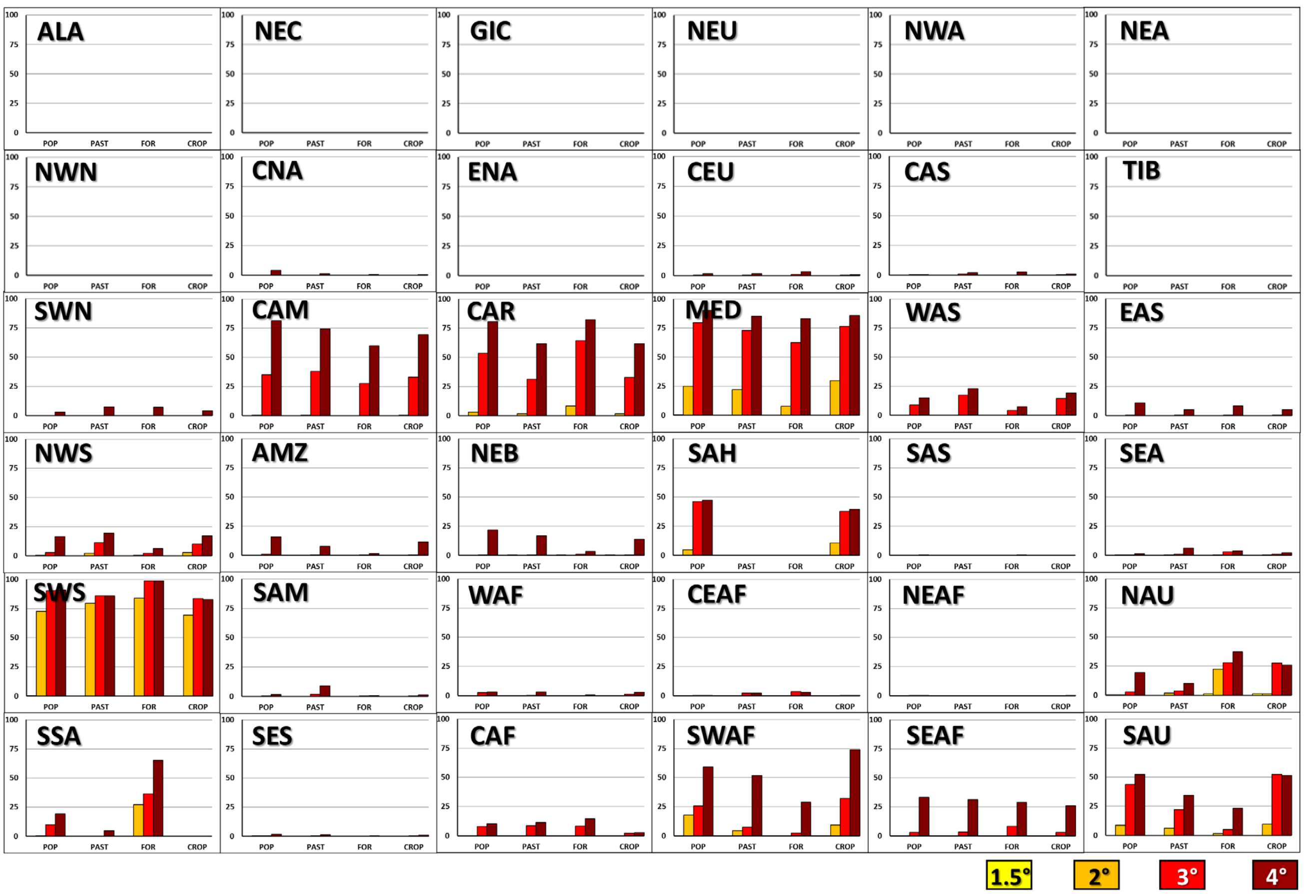

FIGURE 10 Percentage of areas with population and land-use exposed to significant increase in DF, DS and PK for both SPI and SPEI at different GWLs under the SSP5 scenario. See Figure S2 for definition of regions [Colour figure can be viewed at wileyonlinelibrary.com]

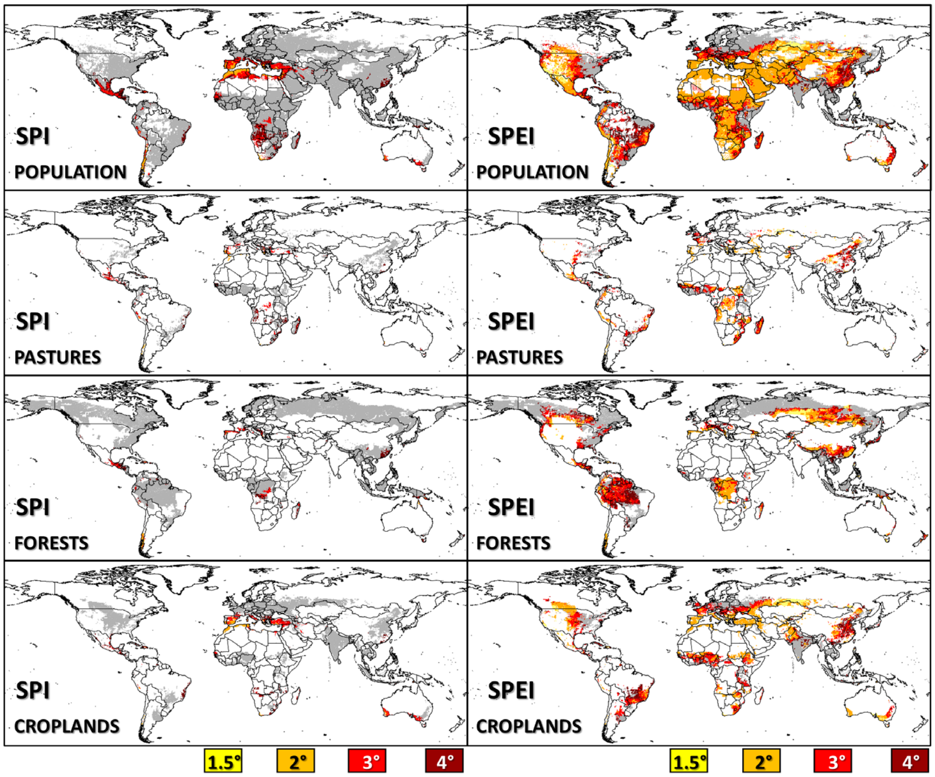

FIGURE 11 Population and land-use progressive exposure to significant increase of both DF and DS at different GWLs under the SSP5 scenario, according to SPI (left) and SPEI (right). White represents areas with population below 1 inhabitant/km^2 and land-use below 5% over the grid point [Colour figure can be viewed at wileyonlinelibrary.com]

Brazil, northeastern Argentina, equatorial Africa, southeastern South Africa and parts of India and Pakistan.

The role of temperature is also clear at the continental scale: for example, in North America for SPI, significant fractions of population and land-use are exposed to an increase in DF and DS only at GWL 3°C and only in southern Mexico, whereas for SPEI, population is already exposed to a significant increase in DF and DS over sparse areas in the United States and Mexico at GWL 1.5°C, progressively extending to southern Canada, most of the United States, Mexico and the Caribbean. In addition, differently than for SPI, forests are projected to be progressively exposed in Canada and the northeastern US and croplands over most of the Mississippi river basin when using SPEI.

4 | CONCLUSIONS

This study builds on a previous study (Spinoni *et al.*, 2020), which focused on GCM and RCM based meteorological drought hazard projections for the end of the 21st century. Here, we extend the analysis to population and land-use exposure to future drought events under five SSPs at viable GWLs. Overall, the drought hazard increases with increasing GWL and more frequent and severe events are projected over large areas of the world, in particular when using the SPEI as drought indicator (Figures 1 and 3). A few drought hotspots can be identified: Central America, southwestern South America, the Mediterranean Region, southern Africa, southeastern China and southern Australia. Most of these hotspots were also noted by Lehner *et al.* (2017), Carrão *et al.* (2018) and Spinoni *et al.* (2020), and recent studies reported on future worsening of drought conditions in central US and Mexico (Wehner *et al.*, 2011; Cook *et al.*, 2015), southern South America (Penalba and Rivera, 2013); southern Europe (Spinoni *et al.*, 2018) and different parts of Africa (Ahmadalipour *et al.*, 2019). The largest increases in drought hazard are likely to occur over regions already vulnerable to this hazard (Carrao *et al.*, 2016), which could consequently have adverse impacts on social and ecological systems (Steffen *et al.*, 2015).

Population and land-use exposure to droughts increases depending on both SSPs and GWLs (Figures 4 and 5). As reported by Smirnov *et al.* (2016) for population, exposure shows small variations with SSPs at moderate GWLs, while at GWLs 3°C and 4°C the differences become larger. According to SPI, population and land-use exposure to drought events is limited in a world following a more sustainable development and not exceeding 2°C of global warming (SSP1 and SSP2) while, according to SPEI, both population and land-use exposure to droughts is remarkable already with these SSPs, and not only with the more severe ones (SSP3, SSP4 and SSP5), where GWLs 3°C and 4°C are reached. Globally, around 2 billion people are likely to be exposed to increased DF and DS (around 5 billion to unprecedented events) when using SPI with any SSP, while with SPEI such values are significantly larger (respectively, 3 and 7 billion people), except with SSP1 (Figure 9; Table 3).

The feedbacks induced by global warming and drought stress are known to reduce plant resilience and increase forest mortality in many regions of the World (Allen *et al*., 2010), impact on crop yields (Parry *et al*., 2005; Li *et al*., 2009; Leng and Hall, 2019) and force farmers to urgent adaptation (Avery *et al*., 2008). The land-use exposed to increased DF and DS is very small or negligible with SPI but large with SPEI, especially with SSP3, SSP4 and SSP5 (Figure 6). However, relevant fractions of all land-use will face at least one unprecedented drought with both SPI and SPEI and any SSP (Figure 7), and at least three unprecedented droughts with SSP5 (Figure S18) and SSP3.

In the last decades, droughts have been increasingly aggravated by heat-waves (Zscheischler *et al*., 2018) and in some cases these phenomena are so strongly connected that excluding temperature from drought analyses could lead to an underestimation of events such as the one in Europe in 2003, which had massive impacts on population, forests and agriculture (Haines *et al*., 2006; Rebetez *et al*., 2006), or the one over Russia in 2010, with large impacts on agriculture and ecology (Loboda *et al*., 2017). If we consider temperature (indirectly included in SPEI), around 50% of global lands will face an increase in DF in the 21st century while, if only precipitation is used as meteorological driver (SPI), this value stays below 10% even at 4°C warming. The use of temperature in drought hazard projections is of particular importance over North America and Asia, where large areas show a positive drought tendency if temperature is considered and a negative one if it is not (Figure 8). Accounting for temperature results in larger population and land-use fractions exposed to droughts with increasing GWL, also due to increased duration of future drought, other than increased frequency and severity (Figure 9).

Investigating droughts with and without temperature as a driver can be of key importance in impact assessments, especially if the effect of precipitation and temperature is considered both separately and in combination, for example on forests (Williams *et al*., 2013; Jeong *et al*., 2014; McDowell and Allen, 2015; Xie *et al*., 2015; Choat *et al*., 2018), crops (Gourdji *et al*., 2013; Zhao *et al*., 2017) and pastures (Perera *et al*., 2019). However, the potential sources of uncertainties are manifold and related to climate simulations (Knutti and Sedláček, 2013; Orlowsky and Seneviratne, 2013; Friedlingstein *et al*., 2014; Dai and Zhao, 2017), population projections (Azose *et al*., 2016) and land-use projections (Prestele *et al*., 2016).

This study focuses on two components (hazard and exposure) of drought risk, with the third component (vulnerability) still needing to be assessed. However, socioenvironmental vulnerabilities to drought for multiple sectors are difficult to quantify even considering single categories like forests (Choat *et al*., 2012), crops or pastures (Wilhite, 1993; Antwi-Agyei *et al*., 2012) or society (Wilhite *et al*., 2019). Comparing vulnerability to droughts among countries is hardly feasible at global scale, because, according to our knowledge, no levelled socioeconomic input database is available for all countries and, in addition, policies to mitigate the impacts of drought can be country specific (Carrao *et al*., 2016). Consequently, a possible preliminary step toward global meteorological drought risk projections could focus on single regions or continents, as done for Africa by Ahmadalipour *et al*. (2019).

The results of this study will be included in the European Commission's Global Drought Observatory (GDO, https://edo.jrc.ec.europa.eu/gdo/) and could be used in drought mitigation and adaptation strategies, which in a global warming context become essential to minimize or cope with the effects of drought impacts (Hagenlocher *et al*., 2019). Knowing where and to what extent land-use is likely to be exposed to increasing drought frequency and severity, country governments and land managers might push for a development based on more sustainable SSPs and plan planting forests and croplands and dislocating pastures in areas less prone to more frequent and severe droughts. Knowing the regions in which population shows progressive exposure to droughts, policy makers could improve infrastructures there and be better prepared for migratory fluxes from over-populated areas likely to face high drought hazard.

Moving from the results obtained, as possible improvements, the drought projections could be updated when the new generation of coupled SSP-RCP simulations will be available at high resolution (Gidden *et al*., 2019), in order to reduce the uncertainties caused by the mixture of climate data based on RCPs and population and land use data based on SSPs. Other drought indicators can be also investigated, for example, soil moisture, usually applied to investigate agricultural droughts (Sheffield and Wood, 2008; Berg *et al*., 2017), for croplands and pastures. For forests, the vegetation response to drought can be tested using remotely sensed data (Cammalleri *et al*., 2016), eventually considering also primary productivity (Vicente-Serrano *et al*., 2013; Xu *et al*., 2019a, 2019b). Moreover, in this study the role of increasing variability in a warming climate has been discussed only marginally, consequently it deserves a special focus in future analyses.

ACKNOWLEDGMENTS

We acknowledge the World Climate Research Programme's Working Groups on Regional Climate and Coupled Modelling, respectively the coordinating bodies of CORDEX and CMIP. We thank all the climate modelling groups that produced and made available their model output. We also acknowledge the Earth System Grid Federation (ESGF) infrastructure, an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling and other partners in the Global Organization for Earth System Science Portals (GO-ESSP). CORDEX data are freely available through the ESGF portal. The authors thank two anonymous reviewers for their constructive comments and suggestions.

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SUPPORTING INFORMATION

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How to cite this article: Spinoni, J., Barbosa, P., Bucchignani, E., Cassano, J., Cavazos, T., Cescatti, A., Christensen, J. H., Christensen, O. B., Coppola, E., Evans, J. P., Forzieri, G., Geyer, B., Giorgi, F., Jacob, D., Katzfey, J., Koenigk, T., Laprise, R., Lennard, C. J., Kurnaz, M. L., … Dosio, A. (2021). Global exposure of population and land-use to meteorological droughts under different warming levels and SSPs: A CORDEX-based study. *International Journal of Climatology*, *41*(15), 6825–6853. https://doi.org/10.1002/joc.7302