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ORIGINAL PAPER

Assessment of drought characteristics and its impacts on net primary productivity (NPP) in southeastern Tunisia

Olfa Terwayet Bayouli[1] · **Wanchang Zhang**[1] · **Houssem Terwayet Bayouli**[2]

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Abstract

Drought ranks among the most damaging natural hazards to ecosystems and human wellbeing alike. Under changing climate context, water-scarce countries like Tunisia are projected to experience droughts in the future at an alarming pace and intensity. Although drought challenges are notably increasing in Tunisia, research devoted to the investigation of their impacts on net primary productivity (NPP) is limited. This study takes a leading role in unraveling NPP responses to droughts in southeastern Tunisia during 2000–2016. The assessment was performed based on the standardized precipitation index (SPI) extracted from long-term observation data and satellite-based annual NPP datasets derived from MOD13Q1 EVI products. Drought events were first identified and their characteristics were analyzed in terms of severity and spatiotemporal variability. Accordingly, we assessed NPP variation and explored the relationship between NPP and droughts at annual timescale through SPI and NPP anomalies. Results revealed that southeastern Tunisia was subjected recurrently to moderate to extreme drought events. The NPP response to droughts in Tunisian arid environments depends mainly on the drought's intensity and duration. Further investigation of the relationship between annual SPI and NPP anomalies depicted that mild and short-time droughts had a lagging effect on NPP. The results foster the importance of arid ecosystems to resist dry periods, underpinning thus their resilience to droughts. Our findings could constitute a scientific basis for regional planners and policy-makers to effectively develop adaptation and restoration strategies to cope with drought impacts and enhance ecosystem services in arid environments.

Keywords Droughts · Standardized precipitation index · MODIS time series · Net primary productivity · Drought lagging effect · Southeastern Tunisia

Introduction

Drought is a ubiquitous natural hazard that tends to be more frequent under changing climate (Pachauri et al. 2014). Described as a slow creeping natural hazard, drought has crosscutting impacts on a broad range of environment and society sectors (Dai et al. 2004; Tian et al. 2020). Droughts refer to water deficit situation relative to normal conditions (Lloyd-Hughes 2014), and they are divided into four categories namely hydrological, meteorological, agricultural, and socioeconomic (Nalbantis and Tsakiris 2009; Tu et al. 2018; Wilhite and Glantz 1985; Wu et al. 2016). Prevalent dry events along with climate change were identified as great challenges to sustainable development in drylands worldwide driving to drier agriculture and more vulnerability to degradation (Banerjee and Pandey 2021; Cervigni and Morris 2016). By 2050, the number of people at hunger risk particularly droughts is expected to increase by 10–20% as a result of climate-related extremes (UNCCD 2014). Thus, drought influences would rationalize ecosystem alteration, disruption of food production, and water supply that ultimately affect human sustenance (Mohammad et al. 2018; Pachauri et al. 2014; Ullah et al. 2019). Additionally, there are strong links between land degradation, water use, and drought. Droughts and water scarcity exacerbate land degradation by intensifying sand and dust storm activity, poor

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✉ Wanchang Zhang
zhangwc@radi.ac.cn

[1] Key Laboratory of Digital Earth Science, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100094, China

[2] National Agronomic Institute of Tunisia (INAT), 43 Avenue Charles Nicolle, 1082 Tunis, Tunisia

irrigation management and drainage, and altered hydrology leading to poorer soil quality (Belal et al. 2014; Reichhuber et al. 2019; Middleton and Kang 2017). Therefore, it is necessary to manage both land and water resources to tackle drought effects and achieve land degradation neutrality and long-term water security. The urgency of this matter mobilized the international communities to adopt assertive actions and policies such as the United Nations Convention on Combating Desertification (UNCCD), Drought Initiative during the 2018–2019 biennium and Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR 2015). These polices promote a wide range of measures aiming drought risk reduction and preparedness. In this context, numerous indices were developed appropriately for each drought type and for particular environment (Zargar et al. 2011) where the most commonly used index is the standardized precipitation index (SPI) which is precipitation-based index (McKee et al. 1993). As a part of north Africa, which are appropriately described as arid and water-scarce region, droughts are a recurrent phenomenon in Tunisia. They are projected to be more frequent at an alarming pace and intensity under global climate change (Nasr et al. 2008; IPCC 2013; Verner et al. 2018). They are featured by water supply scarcity, reduction or disappearance of vegetation cover, soil degradation, and biological diversity decline with drastic effects on local terrestrial ecosystem particularly on net primary productivity (NPP) (Bazza et al. 2018, Chen et al. 2013, Li et al. 2020). NPP is defined as the net carbon amount assimilated after photosynthesis and autotrophic respiration over a given time period (Clark et al. 2001). It is typically represented in kg/ha/year, and it plays a major role in global carbon balance (Sun et al. 2016). Indeed, increasing drought magnitude along with climate change resulted in a reduced NPP worldwide (Chen et al. 2013; Peng et al. 2017, Xu et al. 2020, Zhao and Running 2010). Therefore, the exploration of NPP responses to drought at global and regional scales has recently been the focus of many researchers (Vicca et al. 2016; Vicente-Serrano et al. 2013; Zhang et al. 2016). For example, Peng et al. (2017) revealed that droughts generated 37% of the global NPP decline during recent decades. Similar findings were stated at regional scale in different regions like China (Lai et al. 2018), Europe (Vicca et al. 2016), and Africa (Khalifa et al. 2018). Actually, understanding NPP responses to droughts contributes in developing drought mitigation and management strategies. The results of these studies confirm that droughts induced remarkedly NPP variation (Chen et al. 2013; Zhao and Running 2010). Although Tunisia is a drought-prone country where several drought events have occurred over the last decade, researches devoted to drought effects on NPP are still lacking. Previous studies were focused mainly on specific drought event identification and rainfall regime analysis without taking the relationship between droughts and NPP variation into account. Thus, the impact of the increasing drought intensity and severity on NPP remains undiscussed (Ben Boubaker et al. 2003; Bergaoui and Louati 2010; Chebil et al. 2019). Therefore, this study aims to investigate the connection between droughts and NPP variation in southeastern Tunisia over a 17-year period (2000–2016). Initially, SPI was computed for detecting different drought events and analyzing the spatiotemporal drought distribution in terms of intensity, duration, severity, and location. Then, NPP variation and their responses to droughts in dry ecosystems were investigated. Subsequently, results from this paper could provide a scientific basis for identifying drought nature in southeastern Tunisia and understanding their impacts on local ecosystems productivity. To the best of our knowledge, this is an unprecedented study that unveils the relationship between NPP and droughts in southeastern Tunisia, a distinct that allows developing drought mitigation and management strategies in arid context for better understanding of NPP monitoring to tackle drought impacts on local ecosystems.

Material and methods

Study area

The present study was conducted in Jeffara region which belongs to Medenine governorate in southeastern Tunisia (Fig. 1), located North of the 30th parallel between the Mediterranean and the Matmata mountain chain. The climate is arid with temperate winter (upper arid) in the upper part, while it is arid with a mild winter downstream with irregular rain (lower arid) (Floret and Pontanier 1982; Genin et al. 2006). The study area belongs to a lowly watered zone and receives less than 200 mm/year with about 30 precipitation days with 22 °C mean annual temperature (Genin et al. 2006). The rainfall regime is of Mediterranean type with the rainy season extending from September to April (Ouessar et al. 2009). The soils are developed on a calcareous substratum in the upstream area and gypsum or gypsum to calcareous in the downstream (Genin et al. 2006). The sandy to fine sandy texture vulnerable to all disturbance forms, combined with sparse and stunted vegetation generally composed of *Chamaephytes* steppes, triggers intensively land degradation process (Gamoun 2016). The studied area is part of the main socio-agro-ecological zones of the country where land degradation and droughts are highly pronounced; therefore, it is considered as typical representative of the arid southeastern Tunisia. In response to ongoing degradation problems, sustainable land management (SLM) practices and techniques addressing essentially droughts, soil erosion, and rangeland degradation became an integral part of the southeastern Tunisia landscape (Genin et al. 2006). These SLM practices consisted mainly of soil and water conservation

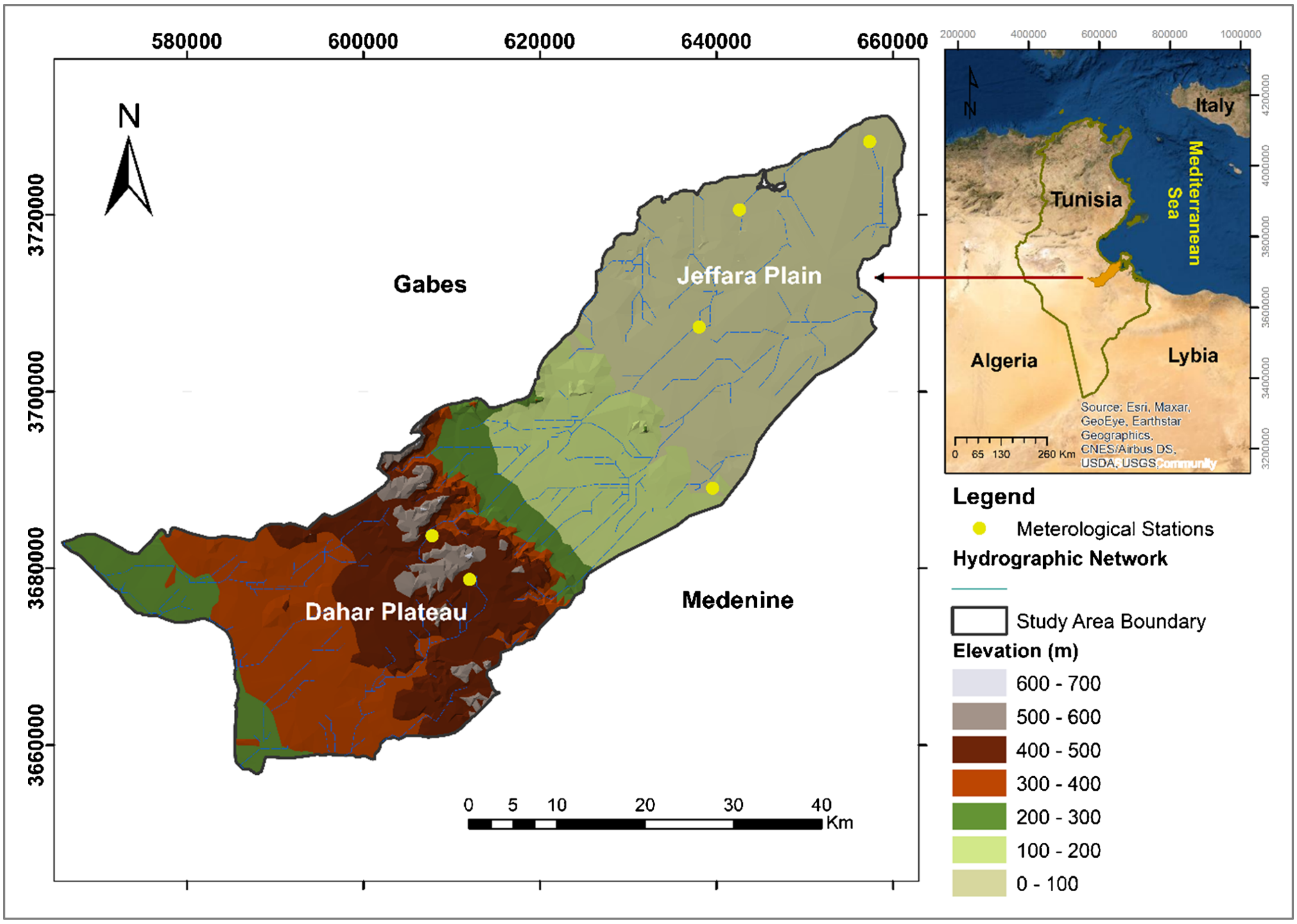


Fig. 1 Location map of the study area with meteorological stations in southeastern Tunisia (Jeffara Region), Medenine Governorate

(SWC) techniques (water harvesting and sand dune fixation) on one hand and rangeland management on the other hand contributing crucially to combat water scarcity and tackling drought impacts (König et al. 2012).

Data collection

Rainfall data

A 21-year historical monthly precipitation record (2000–2016) was used to compute the SPI values (Table 2). The long-term precipitation record was collected from the hydrological databases of the Regional Commissary for Agricultural Development of Medenine from seven rain gauge stations scattered all over the study area.

MODIS data

MOD13Q1 EVI products with 250-m spatial resolution and composed of 15 days were used in investigating drought impacts on NPP. Regarding their capacity for highlighting the spectral response related to green vegetation canopy, a set of 368 images of MOD13Q1 products from 2000 to 2016 (23 images/year) were collected from USGS website. These images were subject to different processing steps under TIMESAT software (Eklundh and Jönsson 2015) to derive a smoothed EVI time series used in calculating, on a pixel basis, annual "small integral" values, serving as proxies for NPP estimates.

Methodology

SPI-based droughts assessment

Drought indices served as useful tools for monitoring different drought types pointing out climate anomalies (Elhoussaoui et al. 2021; Zargar et al. 2011). Numerous indices were widely developed and used for drought events identification (Zargar et al. 2011). In this study, the commonly used drought index SPI was adopted to characterize spatial drought patterns in terms of duration, frequency, intensity, and location and based on the long-term precipitation time series at different time scales from 3 to 24 months (McKee et al. 1993). Regarding temporal flexibility, SPI is useful in both short-term agricultural and long-term hydrological applications (Hua et al. 2019). The SPI calculation method (Eq. 1) follows the Gamma method (Eq. 2) (Dogan et al. 2012; McKee et al. 1993). In this research, we computed SPI at annual timescale from a 21-year historical record of precipitation data (2000–2016) using Meteorological Drought Monitoring (MDM) software package (Salehnia et al. 2017):

$$SPI = \frac{(Pi - Pm)}{S} \tag{1}$$

where Pi is the precipitation of the year i; Pm is the mean precipitation of the study period; S is the rainfall standard deviation during the studied period:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{\frac{-x}{\beta}}, (x > 0) \tag{2}$$

where Γ(α): the gamma function; x (mm): precipitation amount ($x > 0$); α: the shape parameter ($\alpha > 0$); and β: the scale parameter ($\beta > 0$).

Drought characteristics

The fundamental drought characteristics are intensity, duration, frequency, and location (Zhang et al. 2015). In this study, these drought properties were determined for each drought event over the study area along 21-year period.

Mann–Kendall trend test

It is a ranked non-parametric test commonly used to analyze trends in meteorological and hydrological droughts (Mann 1945; Kendall 1975). This test produces z scores providing information on the monotonic trend's significance and direction, where Z score < -1.96: decreasing trend, Z score > 1.96: increasing trend, $-1.96 < Z$ score < 1.96: no change (Onyutha et al. 2016; Fensholt et al. 2013). The Theil–Sen estimator was also used to detect the trend magnitude in hydro-meteorological time series (Lettenmaier et al. 1994). Thus, the MK test and the Sen Slope estimation were employed to determine the existence of trends, their evolution signs, and their statistical significance in the annual SPI series (2000–2016).

Drought mapping

The inverse distance weighting (IDW) is the most common method used for drought spatial extent mapping given its simplicity and intuition (Cavus and Aksoy 2019, Chen et al. 2017, Jahangir and Yarahmadi 2020). In this research, only SPI with negative values were interpolated respecting IDW method and using GIS techniques to derive drought spatial extent. Then, the interpolated maps were reclassified into different drought severity classes according to Table 1.

Drought impacts on NPP

In arid environments, increasing intensity and frequency of drought under climate change could trigger the biodiversity loss and alter ecosystem function by decreasing their NPP (Kath et al. 2019; Tubiello et al. 2007). Recently, droughts have occurred more frequently in Tunisia, and their impacts have been exacerbated by the rising water demand (Verner et al. 2018). Thus, investigating the drought impact on NPP could be advantageous for drought risk management and mitigation also for prediction resilience to extreme climate variability. To this end, NPP was selected as the response indicator of drought to assess its impacts on arid ecosystems of southern Tunisia. Given that NPP is a time-consuming variable and costly to estimate, we relied on remotely sensed information to derive NPP estimates. Enhanced vegetation index (EVI) was then used in this study as NPP surrogate. The EVI was proposed by the MODIS Land Discipline Group (Huete et al. 1999). Bi-weekly products from MOD13Q1 EVI (23 images per year) spanning a 17-year period (2000–2016) were processed under TIMESAT software (Eklundh and Jönsson 2015) to compute EVI annual integrals (Fig. 2). The Logistic curves smoothing filter was applied to EVI time series to reduce noise generated by cloud contamination. Phenological metrics were extracted from the smoothed EVI time series under TIMESAT. An NPP-surrogate (hereafter named NPP) was estimated for each one of the 17 phenological cycles from 2000 to 2016, based on the small integral values, which correspond to the lower integral or to the seasonal productivity (Fensholt et al. 2013; Mao et al. 2015; Olsen et al. 2015). Then, NPP anomalies were computed to assess drought impacts. The NPP Standardized Anomaly Index (NPP-SAI) developed by Pei et al. (2013) was conceived as a good indicator to detect NPP anomalies. It is defined as

$$SAI\ npp = \frac{NPP(i) - \overline{NPP}}{\sigma NPP} \tag{3}$$

where SAI_{npp}: NPP anomalies; $NPP(i)$: the NPP in the year i; $\overline{NPP}$: mean NPP value; and σ_{NPP}: the standard deviation for the NPP.

Table 1 Drought classification based on SPI

Condition	Criterion
Non-drought	$-1 < \text{SPI} < 1$
Moderate drought	$-1.5 < \text{SPI} < -1$
Severe drought	$-2 < \text{SPI} < -1.5$
Extreme drought	$\text{SPI} < -2$

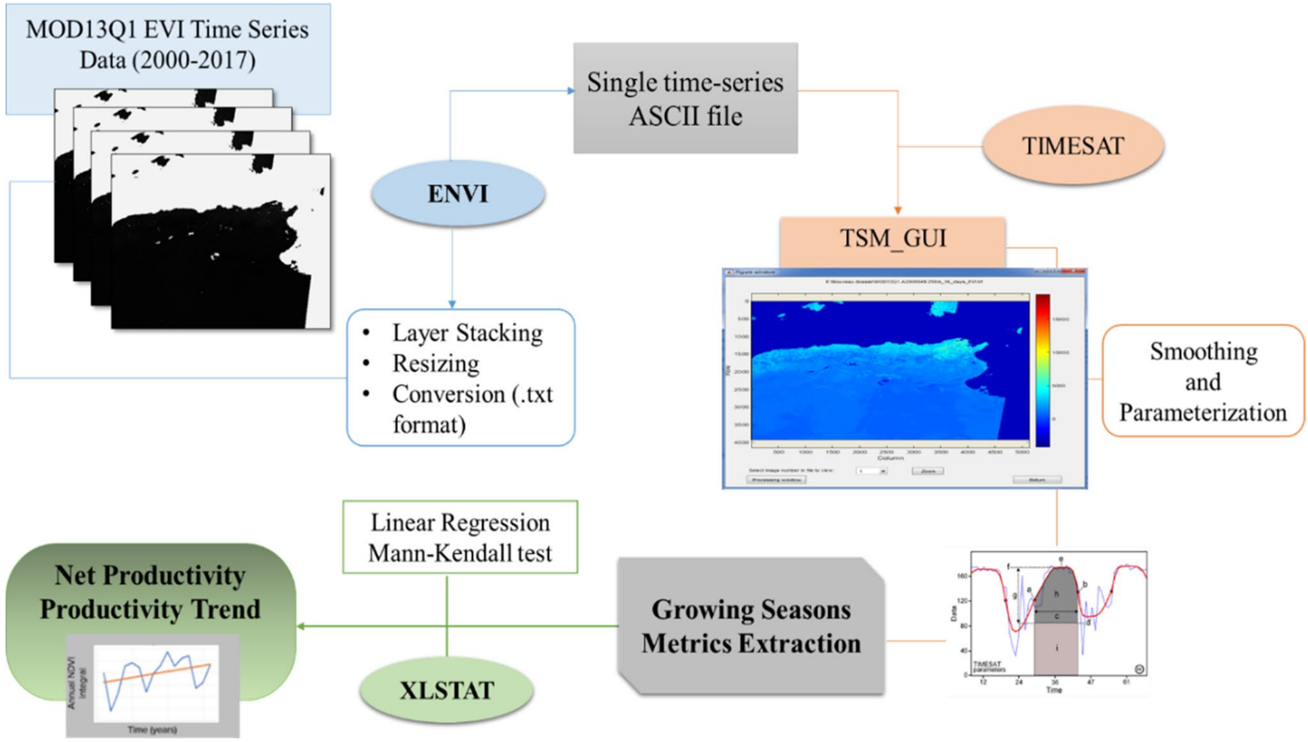


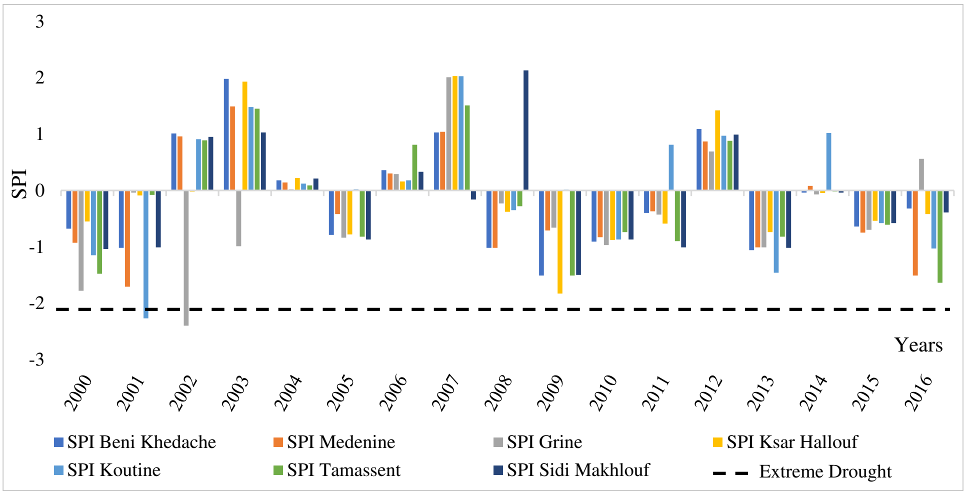
Fig. 2 Methodological flowchart for assessing net primary productivity (NPP) response to drought events; EVI enhanced vegetation index

Results

Spatiotemporal characterization of drought

Given that our study area is confronted to two totally opposite climate types (the Mediterranean and the Saharan climate), the rainfall regime was spatiotemporally irregular. Southeastern Tunisia witnessed recurrent drought events at variant intensity and severity from 2000 to 2016 (Fig. 3). The computed SPI values ranged between – 2.4 and 2.13 with an average of – 0.07, and they represented generally an analogous trend in most of stations. Compared to other years, 2000–2002 was the driest period reported by the majority of the selected stations. During this drought period, the SPI dropped as low as – 2.4 in the upper part of the study area. The total drought-affected areas covered 1135 km^2 being 47% of the entire study area. This result adhered to previous findings (Verner et al. 2018; Jemai et al. 2018) that reported 2000–2002 as the driest period at national scale that engender massive losses in agriculture production (Ghoneim et al. 2017). Therefore, the present results endorsed obviously the IDW method reliability and accuracy (Fig. 4). The drought period was followed by drought-free conditions from 2003 to 2008. The wet climate conditions were witnessed in 2003 and 2007 which depicted dominant positive SPI values that ranged between 1.03 and 2.03 with an exception of two stations in the downstream part (Sidi Makhlouf and Grine) where negative SPI values marked 2003 as a normal year. In 2008, SPI dropped to – 1.02 in Beni Khedache and Medenine stations and distinguished it hence as a moderately dry year. Additionally, the majority of selected stations in Jeffara region exhibited a severe drought condition in 2009 that affected more than 77% of the study area (1854 km^2), pronounced by SPI values between – 0.66 (Grine Station) and – 1.51 (Beni Khedache). A 3-year normal climate period (2010–2012) was recorded except Sidi Maklhouf station which displayed a negative SPI (– 1.01) implying thus a moderate drought condition in 2011. Another moderate drought event was revealed in 2013 spread over 35% of the study region and stated by the majority of stations (– 1.46 < SPI < – 0.74). A 2-year episode (2014–2015) of normal climate came after the moderate drought event of 2011 save the moderate wet event of Koutine station (SPI = 1.02). Although the predominance of normal climate in 2016, negative SPI was depicted across three stations (43%) where SPI dropped to – 1.64 (Tamassent). Hence, a moderate to severe drought condition was bounded in the coastal and central parts (9%) of the Jeffara region.

Fig. 3 Data series of annual SPI from different stations in Jeffara region (Southeastern Tunisia) during 2000–2016



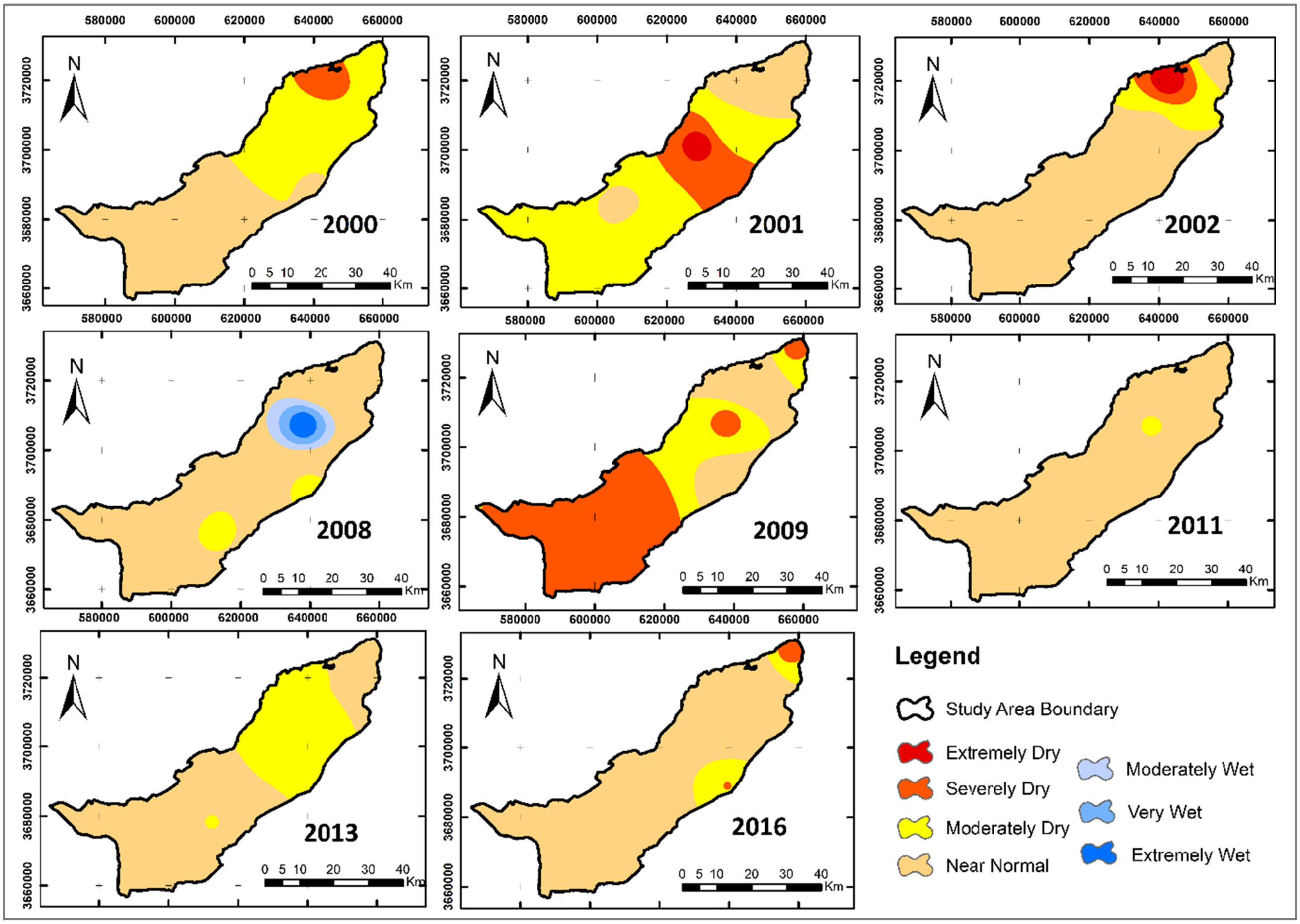


Fig. 4 Spatiotemporal distribution of drought events in southern Tunisia (Jeffara Region) during 2000–2016 period based on SPI values

Drought frequency

Despite the study area having an arid climate, extreme drought and humid events were generally infrequent for all the studied stations. During a 21-year period, SPI calculation revealed only two extremely dry events, whereas severe droughts were marked in all stations accounted for 7%. Moreover, all the studied stations experienced moderately dry events (10%). SPI results showed also extreme wet events (3%) in four stations, very wet events (6%) for five stations, and moderately wet events (8%) for all the stations. The climate was dominantly characterized by normal to near normal years (67%).

Drought trend analysis

In the current research, the trend curve identification was based on SPI values. The results of the Mann–Kendall test and Sen slope estimator are presented in Table 2. The test revealed positive SPI trend values (67%) in most of the stations (Medenine, Grine, Tamassent, and Sidi Makhlouf) displaying increasing trends. However, negative SPI trend values were marked in only two stations (Beni khedache and Ksar Hallouf), exhibiting a decreasing trend. In fact, the upward trend in SPI data values indicated humid climate tendency, while the downward trend points out a dry climate.

NPP results

NPP analysis

Trend analysis was used to unravel variation whether upward, downward, or consistent. The non-parametric Mann–Kendall test revealed trend detection in the NPP-proxies (EVI) observations that did not follow normal distribution of data points. The scatter plot showed a non-significant increasing trend in annual NPP over the period 2000–2016, since the trajectory generated by Mann–Kendall regression figured out a slope (Fig. 5): Z score $= -0.14 > -1.96$ and < 1.96 thus implies no significant change (Sims et al. 2017). Therefore, when conducting the MK linear regression analysis based on "EVI small integrals," notable no significant change ($p = 0.45 > 0.05$) was obtained (Table 2). Although there was a decrease during the extreme droughts period (2000–2002), overall NPP trend was stable from 2002 to 2016. These results coincided with the unified Arab report (2019) indicating that 62% of the total Arabian lands, including Tunisia, had stable NPP since no evident change was occurred during the past decade (UNCCD 2018). However, at global scale, many studies reported a gradual decline in the global NPP trend initiated essentially by droughts (Guo et al. 2012; Lai et al. 2018, Murray-Tortarolo et al. 2016, Peng et al. 2017). In our case, moderate and severe droughts are more frequent than extreme droughts where SPI occasionally exceeded − 2 (only for 2001 and 2002) during the study period. Thus, the drought severity could explain the non-significant overall change of NPP trend from 2002 to 2016. However, during extreme droughts (2000–2001), annual NPP showed a decreasing trend. Therefore, our findings approved that annual NPP decrease in dry ecosystems was mainly driven by drought intensity; this was also concluded by Murray-Tortarolo et al. (2016) and Zhao and Running (2010). For example, Murray-Tortarolo et al. (2016) suggested that arid ecosystems would continue experiencing more severe drought events, leading to a decline of NPP trend. They predicted a global reduction of 10–13% in total NPP by 2100. Therefore, as a part of dry ecosystem,

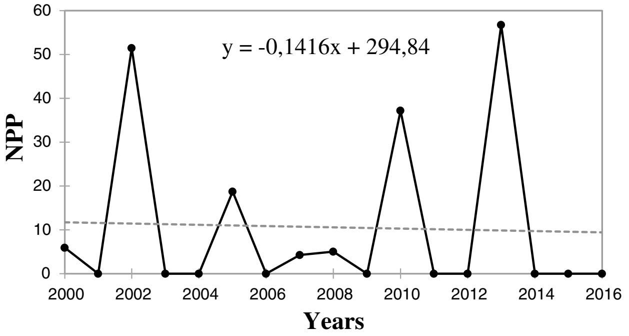


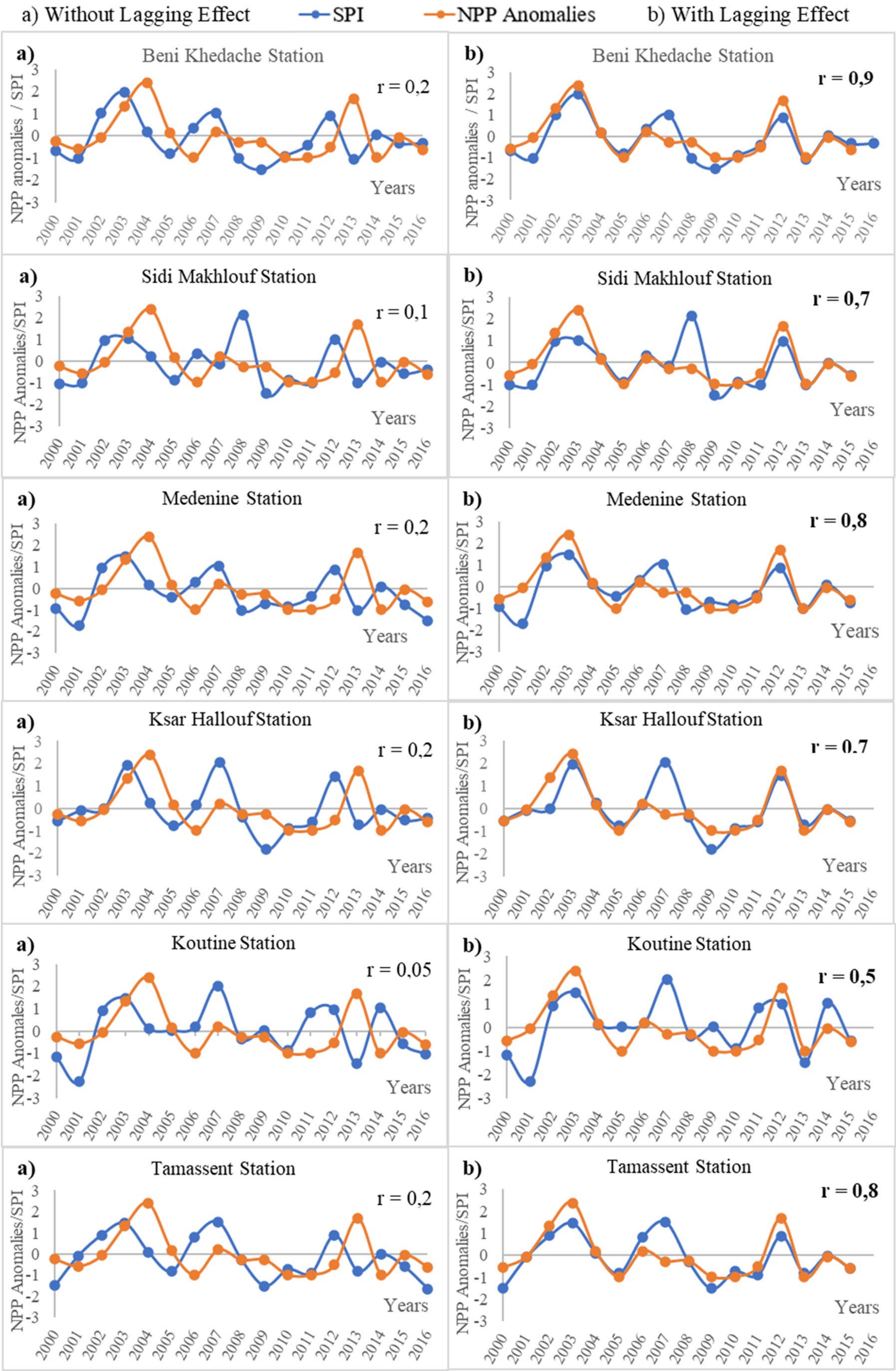
Fig. 5 Productivity trend during 2000–2016 using the Mann Kendall test correlation

Table 2 Mann–Kendall trend Test and Slope Estimators Results of Yearly SPI from 2000 to 2016

Station	Longitude	Latitude	*p*-value*	Kendall tau	Slope estimator
Beni Khedeche	10.2033	33.2458	0.629	− 0.081	− 0.018
Grine	10.5381	33.6194	0.174	0.219	0.058
Ksar El Hallouf	10.1583	33.2908	0.468	− 0.119	− 0.036
Mednine	10.5003	33.3358	0.415	0.133	0.041
Sidi Makhlouf	10.4867	33.5006	0.398	0.138	0.038
Tamassenet	10.6983	33.6869	0.740	0.057	0.016

Positive values indicate increasing trends and negative values indicate decreasing trends

*Non-significant: $p > 0.05$


a) Without Lagging Effect
SPI
NPP Anomalies
b) With Lagging Effect
a) Beni Khedache Station r = 0,2
b) Beni Khedache Station r = 0,9
a) Sidi Makhlouf Station r = 0,1
b) Sidi Makhlouf Station r = 0,7
a) Medenine Station r = 0,2
b) Medenine Station r = 0,8
a) Ksar Hallouf Station r = 0,2
b) Ksar Hallouf Station r = 0,7
a) Koutine Station r = 0,05
b) Koutine Station r = 0,5
a) Tamassent Station r = 0,2
b) Tamassent Station r = 0,8
NPP anomalies / SPI
NPP Anomalies/SPI
Years
3
2
1
0
-1
-2
-3
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016

◂**Fig. 6** Interannual variation of SPI and NPP anomalies (with Pearson's correlation coefficients *r*) without (**A**) and with (**B**) drought lag-effect during 2002–2016 in southeastern Tunisia (Jeffara region)

a declining NPP trend is expected in Tunisian drylands due to recurrent drought events (Murray-Tortarolo et al. 2016, Verner et al. 2018).

Drought impacts on NPP analysis

Decreasing and increasing land productivity detected by vegetation index trends are generally associated to vegetation cover changes, biomass quantity, and to carbon stored quantity in the vegetation. In this study, the EVI datasets were used as proxies for NPP. By means of TIMESAT software, different seasonal information metrics were extracted. Based on our observations, the growth season started when the vegetation index exceeded 50% of the EVI peak (NPP proxy). The season end was flagged when the vegetation index was below 50% of the peak value, based on their small integral's calculation. It reached the maximum usually during the spring season (February, March, April). The main season was detected, starting between late January and mid-February (DOY 37), and the season end was on late-April (DOY 118). The middle of season was observed in mid-March (DOY 104). This season could be associated to spring season when the area became more or less covered by annual vegetation. Another season revealed at the end of the year by December (DOY 336–DOY 354); this season could be related to the rainfall which occurs usually in the autumn. These analyses indicated predominant phenological vegetation behavior in Jeffara region, which had a great biomass gain after a rainfall period. During the 17 seasons brought out from 2000 to 2016, the average NPP was 10.5 with a standard deviation of 18.5. The highest NPP peak (56.7) corresponds to 2013 year. Other high NPP estimates were recorded in 2002 and 2010 with correspondent values of 51.5 and 37.2 kg/ha/year respectively. These NPP peaks could be mainly due to the relatively high rainfall since water availability significantly controlled the NPP (Fernandes et al. 2018; Vicente-Serrano 2006). However, in some years (2006/2009/2011/2014), NPP turned out to zero which could be referred to expansion of bare soils due to drought conditions. In order to further investigate drought effects on NPP, several statistical analyses were conducted. Temporal correlation between SPI and NPP anomalies at an annual scale was first examined over a 17-year span (2000–2016). As indicated by Ji and Peters (2003) and Pei et al. (2013), the correlation between vegetation index and SPI fluctuated from negative to strong. In this study, a weak positive correlation between these two factors in most of cases (from 0.12 to 0.24) was demonstrated. However, for Grine station, the correlation coefficient was negative ($r = -0.1$). As shown in Fig. 6, the highest NPP anomaly peaks were surprisingly corresponding to the lowest SPI values linked to dry years in the majority of stations. Lag effect on NPP appeared in drought events where their impact is visually pronounced each subsequent year. Many other researchers reported the drought delayed effects specifically depending on ecosystem types (Li et al. 2020; Shiba and Apan 2011; Zhao et al. 2020).

Drought lag effect on NPP

The lagging effect of vegetation responses to droughts was examined through correlation analysis. Firstly, a year-to-year comparison between NPP anomalies and SPI was conducted. Then, a comparison between SPI in the current year with the NPP anomaly in the subsequent year was performed. The correlation between NPP and SPI values without considering the lag effect was generally poor (0.05 to 0.24), and it was even negative in Grine (− 0.1). Nevertheless, the correlation coefficients between these two variables significantly increased for all the studied cases when taking the lagging effect into account. For example, in Beni Khedache region, the relationship improved as high as 0.9 (p-value $= 0.003 < 0.05$). Overall, the correlation exhibited a significant relationship between NPP anomalies and SPI explained by positive correlation coefficients fluctuating from 0.5 to 0.9 (p-value < 0.05). Visually, an overall strong positive correlation is observed in most of years (Fig. 6). The SPI and NPP anomalies had a similar trend at an annual scale, where any SPI variations in the current year affect the NPP in the subsequent year. The SPI of 2013 was greatly correlated with the NPP of 2014, where the NPP decreased following the drought year of 2013. Similarly, the SPI of 2009 and 2011 (drought years) were significantly correlated with NPP of 2008 and 2010 respectively, inducing thus an NPP drop. NPP peaks were observed clearly in 2004, 2007, and 2013, coinciding with the SPI of 2003, 2006, and 2012 which were normal to wet years elucidating hence NPP increases. Generally, the NPP decline was associated with the dry condition of the previous year, proving that droughts were the main trigger for the interannual NPP variability in arid environments of Tunisia. Therefore, our results endorsed the insight of drought lagging effect on land productivity in semi-arid and arid environments, stated by previous studies (Huang et al. 2016; Li et al. 2020; Pei et al. 2013; Sun et al. 2016; Vicente-Serrano 2006; Wang et al. 2019), where we found that the response to droughts did not normally occur in the same year when dry condition was proclaimed.

Discussion

Droughts characteristics in southeastern Tunisia

The spatiotemporal analysis of SPI over a 21-year period revealed that the study area was continuously hit by droughts events. Generally, droughts were dispersed most in Jeffara plain region in the eastern direction which had lower topographic relief than the Dahar plateau. These results were consistent with previous researches mentioning that air temperature declined along with the elevation increase which led to higher drought occurrence probability in low-elevation areas (Benavides et al. 2007; Chen et al. 2017; Khalil 2020). Also, it is important to consider the Mediterranean Sea conditions' influence on annual rainfall variability. Considering the spatial pattern of droughts occurrence, it was noted that moderate droughts were more recurrent with more than 10% occurrence probability against 5% for severe droughts. While extreme drought events rarely occurred in the study area with a low probability less than (2%). Previous studies on the spatiotemporal precipitation variability in southern Tunisia and other countries under similar climate condition confirmed the present findings (Ellouze et al. 2009; Feki et al. 2012; Jasim and Awchi 2020; Jemai et al. 2018). Compared to other years, droughts over the consecutive years from 2000 to 2002 were the most severe in terms of duration, intensity, and extent. This drought period might be mainly explained by the intra-seasonal rainfall variation along with the low seasonal mean precipitation. Therefore, it greatly affected the agricultural productivity arising enormous economic losses as mentioned by the FAO report (2016) and other studies (Bazza et al. 2018; Dhaou et al. 2009; FAO 2016; Gargouri et al. 2010; Verner et al. 2018). Similar results were reported earlier in the Mediterranean region and neighbor countries like Italy, Greece, Algeria, and Morocco (Ballah and Benaabidate 2021; Cook et al. 2016; Ezzine et al. 2014; Haied et al. 2017; Rojas et al. 2011) and also in Europe (Bonaccorso et al. 2013).

Drought impacts on NPP variations

Drought impacts on NPP were widely studied across the globe where it was identified that droughts obviously affected the NPP (Peng et al. 2017; Zhang et al. 2016). A drought-induced wide NPP reduction was recorded over Europe (~ 16 gC/m^2/month in 2003) (Ciais et al. 2005; Vicca et al. 2016), southeast Asian countries (30% of NPP decline) (Lai et al 2018; Peng et al. 2017), and south American countries (a reduction of 37%) (Peng et al 2017). At global scale, Chen et al. (2013) confirmed Zhao and Running (2010)'s results who admitted that there was a statistic significant correlation between global NPP and droughts at an annual timescale. In fact, the vegetation response to precipitation deficits was cumulative, and it had a lagging time (Sala et al. 2012; Pei et al. 2013; Peng et al. 2019). In this study, we investigated the NPP variation and local droughts events during the 2000–2016 period at an annual timescale in the arid region based on NPP anomalies. The results of this research revealed that droughts have a lagging effect on NPP. Overall, droughts often induced the NPP decrease at a 12-month timescale, where their impacts are clearly visible in the subsequent year. Our findings confirm therefore the previous studies reporting that drought impacts are reflected in the following months (Khalifa et al. 2018, Li et al. 2020, Liu et al. 2015; Sun et al. 2016, Zhao et al. 2018). Researchers identified that drought lagged effects tend to be more significant at longer timescales (6–12 months) in arid and semi-arid ecosystems (Wang et al. 2020; Sun et al. 2016; Li et al. 2020; Huang and Xia 2019; Huang et al. 2021; Vicente-Serrano et al. 2013; Wang et al. 2021; Xu et al. 2019). Another global study suggested that drought lagging effect could be up to 16–19 months in arid ecosystems (Huang et al. 2016). The current study was conducted in similar climatic conditions in arid context, thereby confirming the drought lagging time.

The Jeffara region has a significant diversity of geomorphological (mountains, heterogeneous foothills and plain) and ecological features (Gamoun 2016). Due to this large variety, the NPP distribution is irregular and depends mainly on regional climate conditions (precipitation and temperature). Despite the detection of negative NPP anomalies, the total NPP trend did not display a significant change during 2002–2016. It showed only a decrease during extreme drought period (2000–2001). A slight NPP increase could be witnessed during mild droughts in arid and semi-arid environments (Khalifa et al. 2018; Sun et al. 2016; Xu et al. 2019). Therefore, we suggest that the annual NPP decrease in dry ecosystems depends mainly on the drought intensity. This result tied strongly also with previous findings of Murray-Tortarolo et al. (2016) and Zhao and Runing (2010).

The vegetation in arid environments had a greater potential to tolerate water deficits with an important resilience capacity owing to strategies namely avoidance and tolerance allowing them to tackle droughts and survive water shortage period (Laity 2009; Knapp et al. 2015). Rangelands are the most dominant land cover category in our study area (Gamoun et al. 2018). They host a rich flora known by their high adaptation to drought conditions (e.g., *Chamoephytes* and *Plantago Albicans*) (Gamoun et al. 2012; Jauffret and Visser 2003). Thus, this vegetation type found evidence for the insignificant change of total NPP trend in response to mild recurrent drought events. Furthermore, olive trees occupy an important place among the local agriculture (about 4 million olive trees on an area of 188,250 ha), and they are mostly rainfed (Laroussi-Mezghani et al. 2016; Sghaier and Ouessar 2013). They are apt to grow in arid environments and resist dry conditions through their deep root system and their water-retention capacity (Dhaou et al. 2009). Thus, they could tolerate short-term water shortages and minimize drought impacts on land productivity (Breshears et al. 2005; Thiery et al. 2017; Vicente-Serrano et al. 2013). Consequently, this could be added to explain the delayed response of local ecosystems to droughts. Furthermore, the local communities have developed for a long time several traditional water harvesting infrastructures namely *Jessours*, *Tabias*, and *Cisterns* (Ouessar et al., 2009). These techniques increased soil water retention underpinning hence their resilience to droughts. Therefore, the NPP response to droughts in Tunisian arid environments is chiefly depending not only on the drought intensity and duration but also on the ecosystem's types and soil management techniques. The current study highlighted also the importance of arid ecosystems to resist dry periods contributing thus to the terrestrial carbon cycle enhancement and ecosystem vulnerability to future droughts.

Other possible factors affecting NPP variation

The drought effects on NPP were obvious where they have been identified as chief trigger of NPP decrease across the globe (Lai et al. 2018; Pei et al. 2013; Zhao and Running 2010). However, other potential factors could be also responsible for NPP variation. For example, heatwaves induce immensely the soil water depletion producing an NPP decrease (Bastos et al. 2013). Southern Tunisia withstood drastic heatwaves in 2007, 2008, and 2013 where the maximum daily temperature exceeded 47 °C. A clear NPP decrease coincided with these heatwaves. Other natural disturbances from meteorological extreme processes and climate variability such as soil erosion, land degradation, and floods could generate different change levels to the growing season start and/or end, to the abnormal warmer or colder period resulting in NPP fluctuation. Furthermore, human activities like land management and LULC conversion were proven to be among the key factors for NPP decline (Li et al. 2020). Hudak (1999) indicated that Africa contributes to 36% of the world's degraded lands stemming from overgrazing. In southern Tunisia, the increasing anthropogenic pressure caused mainly by overgrazing stimulated NPP decline (Gamoun et al. 2015; Le Houérou 2009). Also, the withdrawal of croplands and rangelands in favor of bare soils and urban lands, poor irrigation and land management, and inappropriate farming combined with the climatic aridity could deepen NPP loss. Although, Li et al. (2020) found that human impact on NPP variation was relatively low comparing to drought impacts in a short-term period. This set of indirect effects should be considered in future studies to ensure more accurate NPP variation assessment in response to droughts.

Conclusion

Droughts constitute a major environmental problem in Tunisia. They tend to be more frequent in the future under climate change impact. Yet, the research on droughts, particularly their impacts on NPP, remain lacking and unclear. The studied Jeffara area stretched over different natural regions in the southeastern Tunisia, where clear degradation evidence was apparent feature in these landscapes, coupled with adverse climatological and hydrological conditions. As a consequence, a land productivity reduction was revealed, with substantial ecological damaging effects. The present study initiated the investigation of drought impacts on NPP in southeastern Tunisia where limited insights were provided. The methodological approach was based on the integration of remote sensing and hydrological data. The EVI datasets, from MODIS time series, were used as proxies for NPP integrated with SPI to analyze NPP responses to droughts. This approach allowed the assessment of drought impacts on NPP and the spatial distribution of drought-prone areas in Jeffara region. The spatiotemporal drought analysis exhibited that the study area was recurrently confronted by drought events during the observed period (2000–2016). Droughts were more frequent in Jeffara plain in the eastern direction which had lower topographic relief than Dahar plateau. Despite its aridity, extreme drought events were rare with a restraint probability occurrence less than 2%. However, moderate and severe droughts were more frequent representing higher occurrence probability respectively 10% and 7%. The drought effects on NPP were then analyzed based on annual SPI and NPP anomalies during 2000–2016. As a result, droughts were identified as a main trigger of NPP variation in Tunisian arid ecosystems. The overall NPP trend was stable from 2002 to 2016, except a decrease during extreme droughts of 2000–2001. This highlighted that NPP responses to droughts were mainly depending on the drought's intensity and duration. The key findings of this study exhibited the drought lagging effect on NPP in the Tunisian ecosystems. Generally, droughts induce the NPP decrease at an annual timescale, where their impacts were clearly visible in the subsequent year. The relationship between SPI and the lagged NPP anomalies at a 12-month scale exhibited a significant relationship explained by positive correlation coefficients fluctuating from 0.5 to 0.9 (p-value < 0.05). However, without taking the lag effect into account, the correlation was poor for the majority of the studied stations and even negative for some others. Therefore, knowledge from this study underpins the insight of drought lagged effect on land productivity of arid ecosystems. Therefore, SPI and NPP anomalies served as good indicators for monitoring drought impacts on land productivity. Results of this research constitute a scientific basis for regional planners and policymakers to effectively develop adaptation and restoration strategies and drought management and mitigation plans in arid and semi-arid environments.

Author contribution Olfa Terwayet Bayouli: conceptualization, data acquisition, analysis and interpretation of data and manuscript drafting. Wanchang Zhang: revision, visualization, supervision, and editing. Houssem Terwayet Bayouli: data acquisition, reviewing, editing and proofreading.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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