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Seasonal ecosystem vulnerability to climatic anomalies in the Mediterranean

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Abstract. Mediterranean ecosystems are particularly vulnerable to climate change and the associated increase in climate extremes. This study investigates extreme ecosystem responses evoked by climatic drivers in the Mediterranean Basin for the time span 1999–2019 with a specific focus on seasonal variations, as the seasonal timing of climatic anomalies is considered essential for impact and vulnerability assessment. A bivariate vulnerability analysis is performed for each month of the year to quantify which combinations of the drivers temperature (obtained from ER5 Land) and soil moisture (obtained from ESA CCI and ERA5 Land) lead to extreme reductions of ecosystem productivity using the fraction of absorbed photosynthetically active radiation (FAPAR; obtained from Copernicus Global Land Service) as a proxy.

The bivariate analysis clearly showed that, in many cases, it is not just one but a combination of both drivers that causes ecosystem vulnerability. The overall pattern shows that Mediterranean ecosystems are prone to three soil moisture regimes during the yearly cycle: They are vulnerable to hot and dry conditions from May to July, to cold and dry conditions from August to October, and to cold conditions from November to April, illustrating the shift from a soil moisture-limited regime in summer to an energy-limited regime in winter. In late spring, a month with significant vulnerability to hot conditions only often precedes the next stage of vulnerability to both hot and dry conditions, suggesting that high temperatures lead to critically low soil moisture levels with a certain time lag. In the eastern Mediterranean, the period of vulnerability to hot and dry conditions within the year is much longer than in the western Mediterranean. Our results show that it is crucial to account for both spatial and temporal variability to adequately assess ecosystem vulnerability. The seasonal vulnerability approach presented in this study helps to provide detailed insights regarding the specific phenological stage of the year in which ecosystem vulnerability to a certain climatic condition occurs.

1 Introduction

The Mediterranean Basin is a region particularly threatened by climate change with detrimental impacts on ecosystems (Gao and Giorgi, 2008; Zdruli, 2011; Diffenbaugh and Giorgi, 2012). Moreover, its climate is characterised by great spatial and temporal variability, which makes the investigation of ecosystem impacts challenging. The Mediterranean Basin is marked by complex topography and is influenced by several large-scale atmospheric patterns (Lionello et al., 2006, 2012). Furthermore, it has an intricate seasonal cycle, alternating between water-limited conditions in summer and energy-limited conditions in

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winter (Spano et al., 2013). An assessment of ecosystem vulnerability in the Mediterranean therefore needs to account for both its spatial and temporal variability. It is especially important to investigate the impact of climate extremes on ecosystems, not only mean behaviour, because relationships between climatological and ecological variables at the tails of the distribution can show distinctly different behaviour compared to the findings based on conventional linear correlation (Jentsch et al., 2007; Baumbach et al., 2017; Ribeiro et al., 2020). Thus, it is crucial to systematically investigate the impacts of climate extremes on ecosystems in the Mediterranean.

In this study, we build on the ecosystem vulnerability analysis proposed by van Oijen et al. (2013, 2014); Rolinski et al. (2015), adapted with a focus on seasonal and multivariate impacts using remote sensing and reanalysis data. We enhance the ecosystem vulnerability concept with a focus on the seasonal timing of impacts. Ecosystem responses differ depending on the seasonal timing of the event (de Boeck et al., 2011; Smith, 2011; Sippel et al., 2016). Shifts of only a few weeks in drought occurrence can make the difference between negligible and detrimental impacts (Denton et al., 2017; Sippel et al., 2017, 2018). Even though accounting for seasonality is crucial in investigating climatic impacts on ecosystems, it is still often neglected (Piao et al., 2019). Studies are frequently limited solely to particular periods of interest within the year when investigating seasonality (van Oijen et al., 2014; Baumbach et al., 2017; Nicolai-Shaw et al., 2017; Karnieli et al., 2019), but rarely investigate the seasonality year-round. In addition, combinations of climatic events in the seasonal cycle are seldom addressed (Smith, 2011; Hatfield and Prueger, 2015). Due to the pronounced land-atmosphere feedback mechanisms in the Mediterranean (Seneviratne et al., 2006; Green et al., 2017; Tramblay et al., 2020), it is particularly important to analyse the impacts of climatic anomalies in soil moisture and temperature jointly rather than in isolation (Mueller and Seneviratne, 2012). Such joint impacts of multiple stressors on ecosystems are still little researched (Shukla et al., 2019).

Soil moisture is a particularly relevant variable for assessing the state of ecosystems as it is directly related to plant activity, biomass and agricultural yields (McWilliam, 1986; Sherry et al., 2008; Seneviratne et al., 2010; Zscheischler et al., 2013), especially in water-limited areas such as the Mediterranean (Szczypta et al., 2014). However, large-scale soil moisture data covering long time spans is scarce. Therefore, soil moisture proxies are applied in most cases, e.g. land surface models or drought indicators such as the SPI (Dorigo et al., 2017; Nicolai-Shaw et al., 2017). However, the SPI is primarily an indicator for meteorological droughts, which do not necessarily propagate into soil moisture droughts (de Boeck et al., 2011). Only a few studies use soil moisture data derived from satellite imagery because long-term coverage was not available until recently. Individual satellites do not cover sufficiently long time spans. However, this can be achieved by merging soil moisture data from several satellites. The European Space Agency's Climate Change Initiative (ESA CCI) soil moisture data set provides a unique, globally consistent multi-decadal time series based on several active and passive microwave sensors (Dorigo and de Jeu, 2016; Dorigo et al., 2017). It has proven capability to assess land-vegetation-atmosphere dynamics (de Jeu and Dorigo, 2016; Dorigo and de Jeu, 2016; Nicolai-Shaw et al., 2017; Gruber et al., 2019). So far, satellite-based soil moisture data are still rarely used in ecosystem research (Dorigo et al., 2017), and e.g. Rolinski et al. (2015) point out the need to use observational data in the assessment of ecosystem vulnerability. Therefore, we seek to put greater emphasis on the possibilities arising from newly available remote-sensing products within the last years.

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This study aims to quantify ecosystem vulnerability by assessing which combinations of climatic drivers lead to extreme reductions in ecosystem productivity in the Mediterranean Basin using a bivariate vulnerability analysis with a specific focus on seasonal variations. Soil moisture and temperature are investigated as climatic drivers, and the fraction of absorbed photosynthetically active radiation (FAPAR) is used as an indicator of ecosystem productivity. Furthermore, ecosystem vulnerability is calculated separately by land cover class and subregion to account for the spatial complexity of the Mediterranean Basin.

2 Methods

2.1 Study area

The study area is constrained to all grid points in the Mediterranean Basin belonging to the Köppen-Geiger classes Csa ("Warm temperate climate with dry and hot summer") and Csb ("Warm temperate climate with dry and warm summer")(cf. Fig. 1). Furthermore, the study area is subdivided into land cover classes and subregions. The land cover classes were aggregated according to Table B1 using the ESA CCI land cover classification map of 2018. Pixels where the land cover changed between 1999 and 2018 were excluded in this study, as well as pixels belonging to the land cover classes "Water bodies" and "Urban areas". The countries belonging to each subregion are listed in Table B2.

2.2 Data

Daily satellite-based soil moisture data from ESA CCI was obtained at a resolution of 0.25°from 1978–2019 (Gruber et al., 2019). The merged data set (v04.7), containing data from both active and passive sensors, is used. The quality of this data set has continuously improved over the years due to the incorporation of an increasing number of satellites (Dorigo et al., 2017). The data set is representative for the topsoil surface layer of up to 2 cm thickness (Kidd and Haas E., 2018). Monthly air temperature and soil moisture reanalysis data are retrieved from ERA5 Land produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) at a resolution of 9 km from 1981–2019. (Copernicus Climate Change Service, 2019). ERA5 Land uses the land-surface model HTESSEL, which provides soil moisture in four layers (Hersbach et al., 2020). Only the top layer of soil moisture from 0–7 cm is used in this study. This study is conducted using the ESA CCI soil moisture data set as well as the ERA5 Land soil moisture data set to verify the robustness of our results. The FAPAR is obtained from the Copernicus Global Land Service (CGLS) (Baret et al., 2013; Verger et al., 2014). It is derived from SPOT/VGT from 1999–2013 and PROBA-V from 2014–2019 and is provided in ten-day steps (Verger et al., 2019). Furthermore, the ESA CCI land cover classification for the years 1999 and 2018 with a spatial resolution of 300 m (v2.1.1) were used (ESA, 2017). The Köppen-Geiger classification map was acquired from Kottek et al. (2006) and Rubel et al. (2017).

The Mediterranean Basin is both temperature-limited during winter and moisture-limited during summer (Spano et al., 2013), therefore temperature and soil moisture are investigated here as the key drivers of Mediterranean climate. The FAPAR is investigated as the ecosystem variable here. It is a dimensionless variable, ranging from 0 to 1. It is crucial for monitoring climatic impacts on terrestrial ecosystems and is directly related to the photosynthetic activity of vegetation and thus to its

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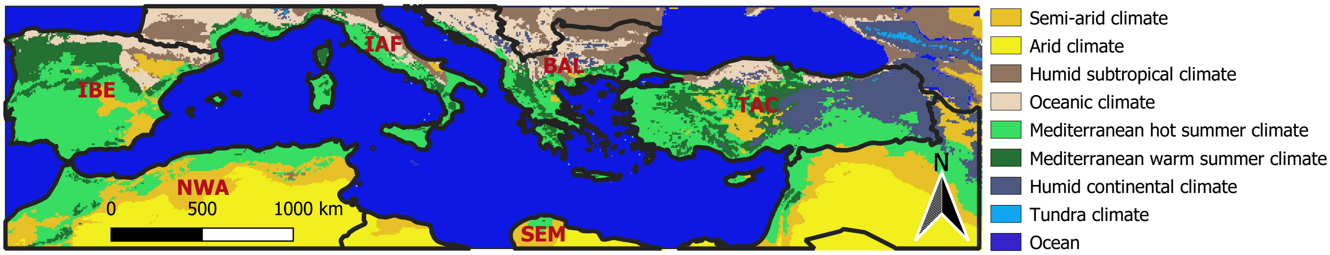

Figure 1. Study area in the Mediterranean Basin: The Köppen-Geiger climate categories "Mediterranean hot summer climate" (light green) and "Mediterranean warm summer climate" (dark green) are included in this study. The study area was divided into six subregions: the Iberian Peninsula (IBE), Italy and France (IAF), the Balkan Peninsula (BAL), Turkey and Cyprus (TAC), the southeastern Mediterranean (SEM) and northwestern Africa (NWA)

greenness and health (Potter et al., 2003; Gobron et al., 2010; Ivits et al., 2016). Vegetation indices such as the NDVI are closely related to the FAPAR and can be seen as proxies (Myneni and Williams, 1994; Pinty et al., 2009).

The ESA CCI soil moisture product (v0.1) was first published in 2012 and has continuously improved since (Dorigo et al., 2017). Since this product merges data from various sensors, it provides a time series of remarkable length (Dorigo et al., 2017).

Satellite-based soil moisture and FAPAR are recognised as important variables for terrestrial earth observation and are part of the essential climate variables (ECV) according to the Global Climate Observing System (GCOS) (GCOS-138, 2010; Dorigo et al., 2017; Smets et al., 2019).

2.3 Data preprocessing

All data sets are resampled to a common spatial and temporal resolution of 0.25° and a monthly time step, respectively. The investigated time span encompasses 21 years from 1999–2019. Pixels with more than 60 months of missing soil moisture data within the period from 1999–2019 were excluded from this study (see Fig. 2). These are primarily pixels located close to the coast. In a next step, all variables are deseasonalised by subtracting the annual cycle to account for extremeness relative to the respective time of the year. The variables are z-transformed by subtracting the monthly mean and dividing by the standard deviation of the deseasonalised time series to allow for direct comparison of values despite their different physical units (Eq. (1)).

$$z_i = \frac{X_i - \mu_{i,month}}{\sigma_i} \tag{1}$$

The impact of environmental drivers on ecosystems may show a time lag of up to a few months – so called "legacy effects" (von Buttlar et al., 2018; Piao et al., 2019). Hence, a moving average of three months $n = 3$ is applied to the environmental driver variables env temperature and soil moisture, i.e. the preceding two months are included with equal weight for each monthly time step i in the time span of $m = 21$ years (Eq. (2)) to account for lagged effects.

$$env_i = \frac{1}{n} \sum_{k=i-2}^{i} env_k \text{ for } i \in (1, ..., m \times 12) \tag{2}$$

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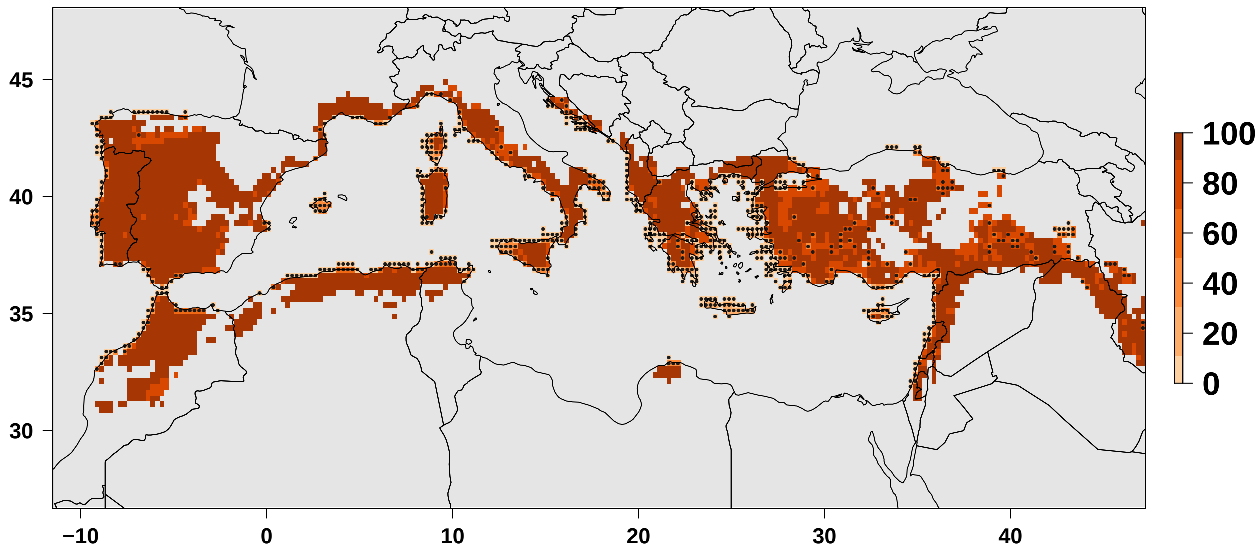

Figure 2. Percentage of available monthly soil moisture values from 1999–2019. All pixels excluded from this study are marked with a dot.

2.4 Derivation of ecosystem vulnerability

The ecosystem vulnerability methodology serves to attribute drivers to their impact and identify whether a univariate or bivariate driver can be attributed to the respective impact. The terminology on ecosystem vulnerability is confusing since several partially ambiguous terms exist due to the concept being still rather new in ecological research (van Oijen et al., 2013; Weißhuhn et al., 2018). Following the definition by Rolinski et al. (2015), "ecosystem vulnerability V_E is the average deviation of the environmental variable under hazardous ecosystem conditions from values under non-hazardous ecosystem conditions" in our approach. In our case, the environmental variable env is either temperature or soil moisture, respectively, and the ecosystem variable sys is the FAPAR. Ecosystem vulnerability V_E is calculated according to Eq. ((3) as the difference of the expectation value E_{nonhaz} of the environmental variable env under non-hazardous conditions of the ecosystem variable sys and the respective value E_{haz} under hazardous conditions of the ecosystem variable sys (van Oijen et al., 2013; Rolinski et al., 2015).

$$V_E = E(env|sys\,\mathrm{nonhaz}) - E(env|sys\,\mathrm{haz}) \tag{3}$$

with conditional expectational values defined follwing Eq. ((4)

$$E(env|\circ) = \int env\,\mathbb{P}(env|\circ)\,\mathrm{d}\,env \tag{4}$$

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where $\mathbb{P}$ is the probability of env under the specified condition $\circ$ ($sys\,\text{nonhaz}$ or $sys\,\text{haz}$). The probability of hazard occurrence $\mathbb{P}_H$ is given by the number of data points under hazardous conditions N_{haz} divided by the total number of data points N, which gives $\mathbb{P}_H = N_{\text{haz}}/N$. The discrimination threshold between non-hazardous and hazardous ecosystem conditions is set as the 10^{th} percentile of the FAPAR values for each grid point individually, i.e. $\mathbb{P}(sys\,\text{haz})$ is fixed to 0.1 in this study. Such a threshold is commonly used in ecoclimatological studies (Ahlström et al., 2015; Baumbach et al., 2017; Nicolai-Shaw et al., 2017). To investigate the robustness of our results, we also performed the analysis using the 5^{th} and 15^{th} percentile for discrimination of hazardous and non-hazardous ecosystem conditions. The spatial and temporal patterns for these cases were in agreement with the 10^{th} percentile chosen in our study (results not shown), which indicates that our results are not sensitive to the choice of the percentile. Our approach is impact-based, i.e. it focusses on the extremeness of the impact rather than the extremeness of the driver because this enables relating multiple drivers to a single outcome (Zscheischler et al., 2014, 2018).

We used the Mann-Whitney U test to investigate significant deviations of climatic conditions during non-hazardous and hazardous ecosystems conditions, which was adjusted for multiple testing using the Benjamini and Hochberg (1995) correction. Significant positive values indicate ecosystem vulnerability V_E to cold (dry) conditions for the climatic driver temperature (soil moisture). Similarly, significant negative values are associated with vulnerability to hot (wet) conditions. In the case of two climatic drivers, this leads to nine possible vulnerability conditions (see Fig. 3). The corresponding p-values are not shown throughout the article due to the large amount of data. A schematic display of the calculation of ecosystem vulnerability V_E is given in Fig. 4 for an exemplary pixel with vulnerability to hot and dry conditions for the month of July. The two drivers temperature and soil moisture are assessed for their effects on ecosystem vulnerability. In this example, the average temperature in July during non-hazardous ecosystem conditions E_{nonhaz} is lower than the average during hazardous ecosystem conditions E_{haz}, leading to a negative vulnerability to temperature, i.e. vulnerability to hot conditions (Fig. 4(a)). For soil moisture, the average soil moisture during non-hazardous ecosystem conditions E_{nonhaz} is higher than soil moisture during hazardous conditions E_{haz}, therefore vulnerability is positive, indicating vulnerability to dry conditions (Fig. 4(b)). The analysis was carried out using R version 3.6 and Climate Data Operators (CDO) version 1.9.

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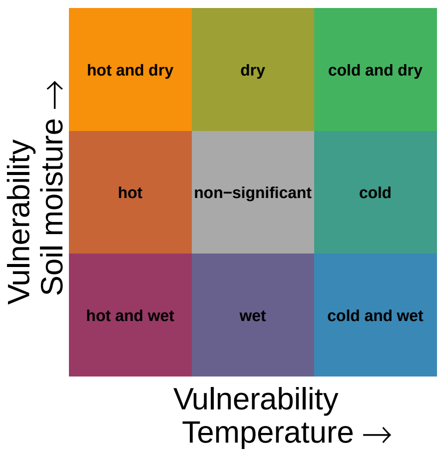

Figure 3. Illustration of the vulnerability to all potentially occurring climatic conditions.

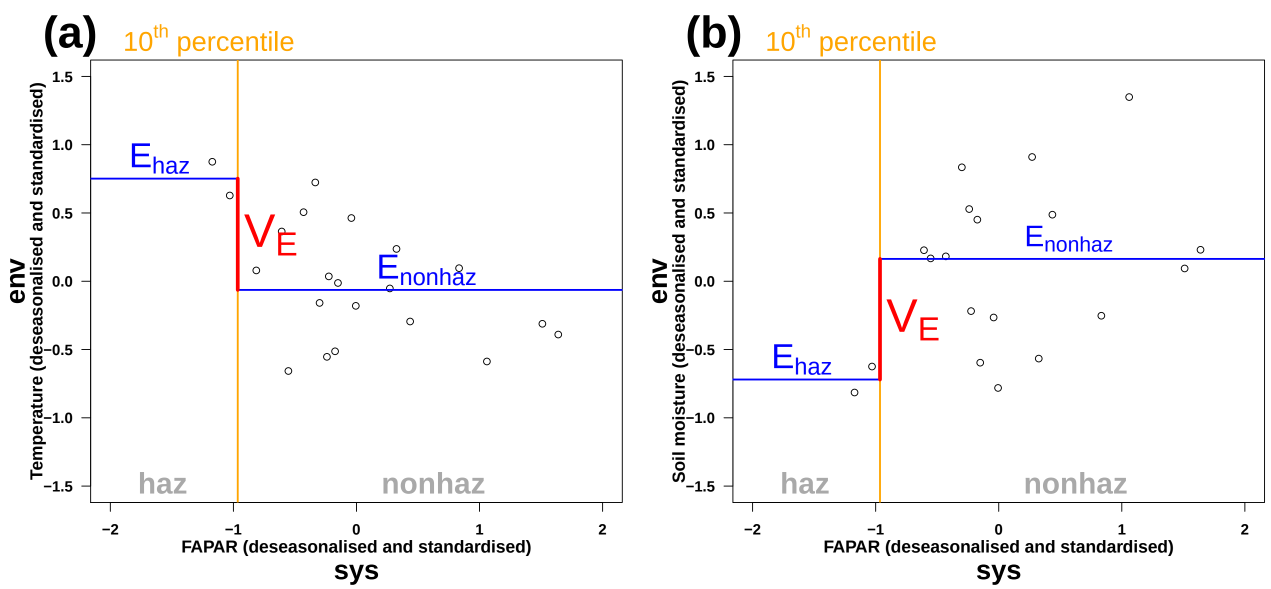

Figure 4. Schematic display of ecosystem vulnerability V_E for an exemplary pixel for (a) temperature and (b) soil moisture as environmental driver for the month of July.

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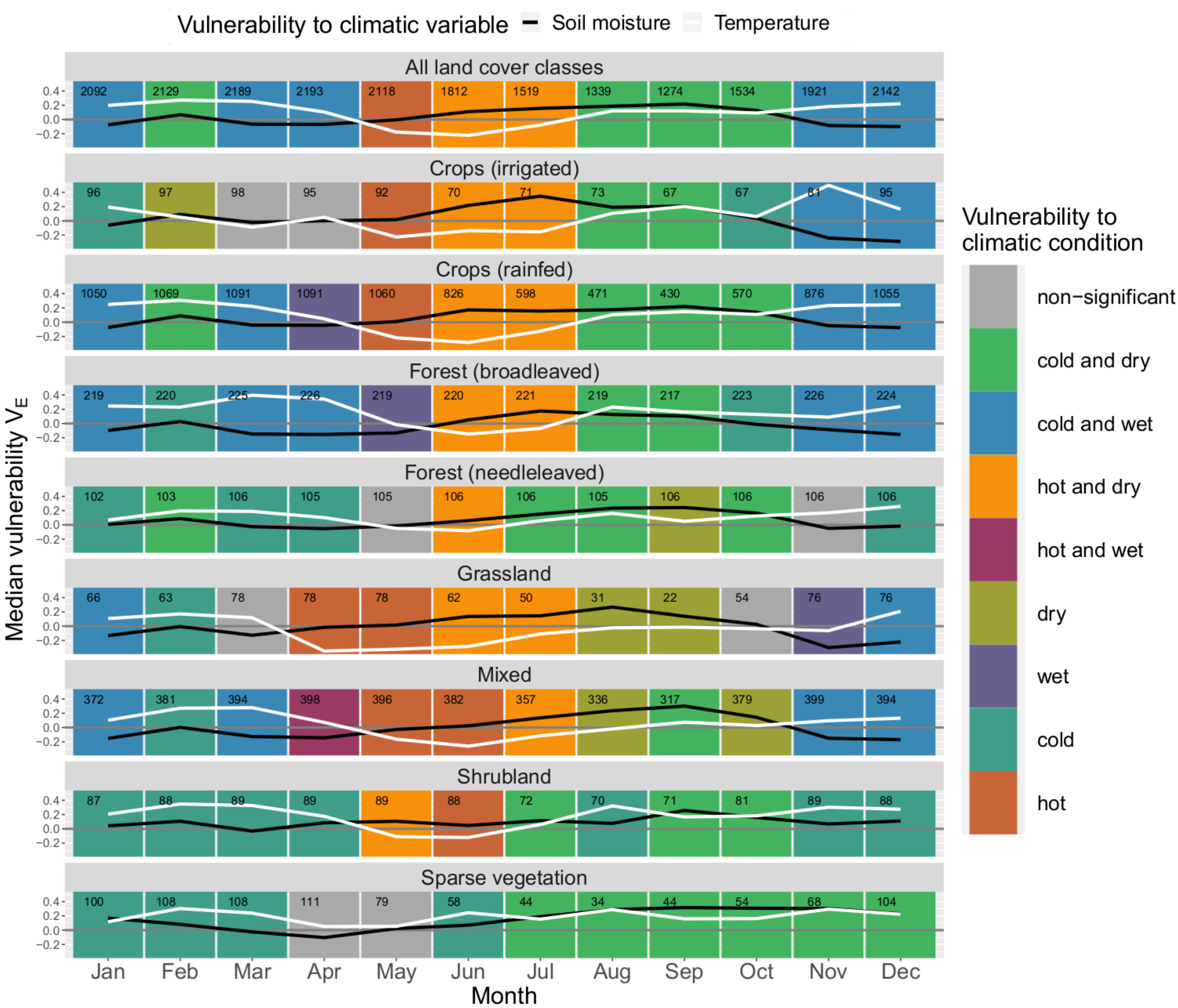

Figure 5. Median monthly ecosystem vulnerability per land cover: Vulnerability to temperature (ERA5 Land) is shown in white and vulnerability to soil moisture (ESA CCI) is shown in black for each month of the year (columns) for each land cover (rows). Months with statistically significant deviation of climatic drivers during non-hazardous and hazardous ecosystems conditions according to the Mann-Whitney U test based on a significance level $\alpha = 0.05$ are shown in colour (see legend), all other months are shown in grey. The number of pixels in which an event has occurred in this month and land cover within the period 1999-2019 is shown in the upper left corner of each panel.

3 Results

3.1 Ecosystem vulnerability by land cover

Figure 5 displays the ecosystem vulnerability to soil moisture and temperature for each land cover class and each month of the year, as well as the corresponding statistical significance as background colour (see explanation in Fig. 3). The vulnerability to

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temperature and soil moisture can be summarised into three major regimes during the course of the year (see Fig. 5). From May to July, the vegetation is especially prone to hot and dry conditions. From August to October, there is a shift to a vulnerability to cold and dry conditions in general. Finally, from November to April cold and wet conditions are usually associated with high vulnerability of the vegetation. There are sharp transitions in ecosystem vulnerability from April to May, from July to August, and from October to November for most land cover classes.

In the period from November to March the vast majority of land covers is vulnerable to cold conditions. From March to May there is a transition phase from cold to hot conditions. While in March almost all land covers are vulnerable to cold conditions, in April only three of them still remain vulnerable ("Forest (broadleaved)", "Forest (needleleaved)" and "Shrubland") and none are vulnerable in May, when the majority shifts to vulnerability to hot conditions. In summer, a period with significant vulnerability to hot conditions only often precedes the next phase of vulnerability to both hot and dry conditions, indicating that the heat desiccates the soil first until it reaches critically low soil moisture levels in the following months. The cycle reverses around July and August. While five land cover classes are still vulnerable to hot conditions in July, none of the classes are in August. Vulnerability to high temperatures is almost entirely restricted to the period from May to July. From August to October, most land cover classes exhibit vulnerability to cold and dry conditions, and from midsummer to the beginning of autumn almost all land cover classes are prone to drought. In the following period from November to March, cold and wet conditions prevail on average. The vulnerability to wet conditions is highest from November to January , whereas many land cover classes are insensitive to soil moisture during most of the time from February to May. Exemptions are e.g. "Forest (broadleaved)", "Crops (rainfed)" and "Mixed", where low ecosystem productivity coincides with wet conditions e.g. in March to April.

The vulnerability to hot conditions of "Grassland" is one month ahead of most other land classes, starting already in April. This could indicate a faster response of this land cover class to environmental drivers than other land cover classes. Sparse vegetation never shows vulnerability to hot conditions, meaning that it is probably well adapted to such temperatures. It also never coincides with significantly wet conditions, which might point out that transpiration in these areas is never so high that it could contribute substantially to the desiccation of the soil and thus its influence on soil moisture is negligible.

3.2 Ecosystem vulnerability by subregions

Similarly to Fig. 5, ecosystem vulnerability for each subregion is shown in Fig. 6. There is more variability than regarding land cover classes and the general pattern of most land cover classes with a "hot and dry" regime followed by a "cold and dry" regime and subsequently by a "cold and wet" regime does not hold true for most of the Mediterranean subregions. The vulnerability to soil moisture usually peaks during summer or autumn and reaches a minimum in spring – exceptions are Italy and France as well as the southeastern Mediterranean. The yearly development of vulnerability to temperature is characterised by a minimum around late spring or summer.

There is an extended period of time in which ecosystems are prone to hot conditions from March to October in Turkey, whereas in other regions this period often only lasts for two to three months in spring and summer. In northwestern Africa, Turkey and the southeastern Mediterranean, wet conditions coincide with ecosystem vulnerability only during up to three

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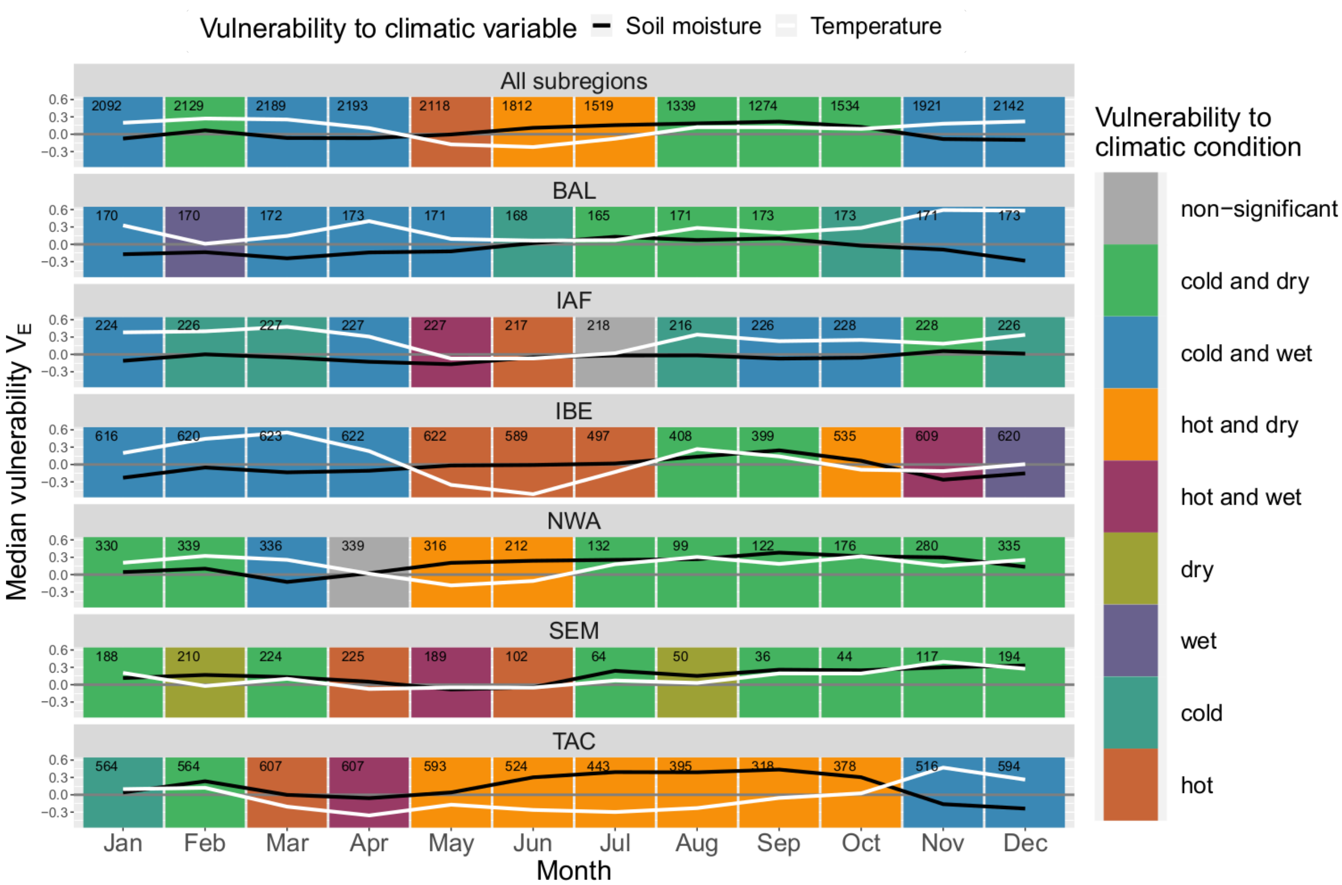

Figure 6. Median monthly ecosystem vulnerability per subregion: Vulnerability to temperature (ERA5 Land) is shown in white and vulnerability to soil moisture (ESA CCI) is shown in black for each month of the year (columns) for each land cover (rows). Months with statistically significant deviation of climatic drivers during non-hazardous and hazardous ecosystems conditions according to the Mann-Whitney U test based on a significance level $\alpha = 0.05$ are shown in colour (see legend), all other months are shown in grey. The number of pixels in which an event has occurred in this month and subregion within the period 1999-2019 is shown in the upper left corner of each panel.

months in the course of the year, indicating that these regions are usually soil-moisture limited. The southeastern Mediterranean is prone to dry conditions almost year-round. Italy and France have the lowest sensitivity to soil moisture with only small deviations from zero. Nevertheless, these deviations are significant for half of the months in the year. Interestingly, the Balkan Peninsula is never prone to hot conditions. Outside of the summer season, wet conditions particularly coincide with low ecosystem productivity in Italy and France, the Balkan and the Iberian Peninsula.

The number of events per month is not equally distributed throughout the year. There is a decline from June to November with a minimum usually around September in which only few events are detected. This reflects the time span of the dormant season since these months are usually too dry for ecosystem activity. There are some notable exceptions for land covers

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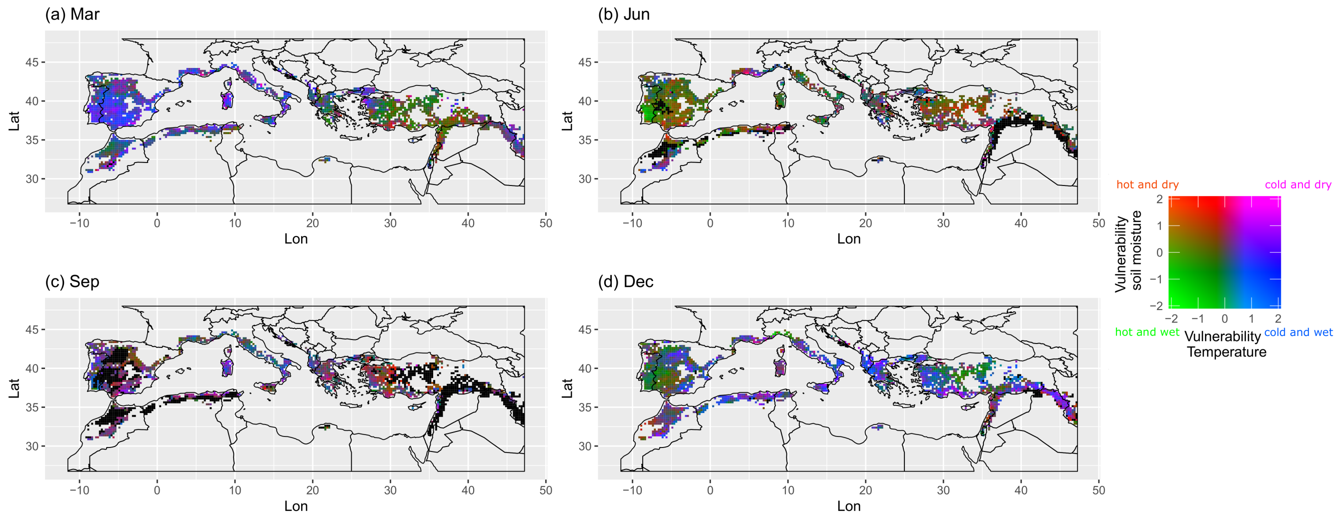

Figure 7. Average monthly vulnerability to soil moisture (ESA CCI) and temperature (ERA5 Land) in the Mediterranean Basin for (a) March, (b) June, (c) September and (d) December. Pixels without any events during the respective month are displayed black.

involving trees (“Forest (broadleaved)”, “Forest (needleleaved)”, “Mixed” and “Crops (Irrigated)”)(see Fig. 5), as well as the most northern subregions of the Mediterranean, Italy and France and the Balkan Peninsula (see Fig. 6), where the number only decreases slightly during this period. These land cover classes and subregions are less affected by the characteristic dry period in summer. Forests have better access to soil moisture because they develop deeper roots (Bréda et al., 2006; Zhang et al., 2016), whereas irrigated areas obviously have an external water supply. The northern subregions are also moister than the southern Mediterranean.

Satellite-derived soil moisture data sets are prone to uncertainty, even though there have been considerable improvements in the last years (Gruber et al., 2019). Therefore, ecosystem vulnerability was also assessed for all land cover classes and subregions using ERA5 Land reanalysis soil moisture in addition to ESA CCI soil moisture to verify the robustness of our results and whether specific biases are apparent (see Appendix A).

The spatial patterns of ecosystem vulnerability are displayed for four exemplary months of the year (see Fig. 7), whereas all twelve months can be found in the Appendix (see Fig. B1). In March in most western Mediterranean regions, low FAPAR values are associated with cold and wet conditions (blue colouring), whereas in the eastern Mediterranean vulnerability to hot conditions (green and red colouring) is already emerging at this time of the year. In June, almost all regions are vulnerable to hot conditions and often also to dry conditions (green and red colouring) with exceptions in the northernmost regions such as the French Riviera, as well as mountainous regions such as the Peloponnese in Greece and the High Atlas in central Morocco. In September, there are often no low FAPAR anomalies occurring (black colouring) particularly in southern and inland regions, which are the hottest regions of the Mediterranean. The reason for this is that this time usually corresponds to the dormant season in these areas. In regions where events are detected during this time of the year, vulnerability to cold and dry conditions (purple colouring) prevails in most of the Mediterranean, with the notable exception of Turkey, which is vulnerable to hot and dry conditions (red colouring). In December, in most areas in the central Mediterranean, low FAPAR values coincide with cold and wet conditions (blue colouring), whereas in central Turkey and the southern Iberian Peninsula vulnerability to hot and wet conditions (green colouring) occurs.

4 Discussion

4.1 Interpretation of temporal and spatial patterns in the Mediterranean

Our findings are in accordance with the characteristics of the Mediterranean climate regime, which is primarily energy-limited during winter and soil moisture-limited during summer (Schwingshackl et al., 2017). The vulnerability analysis allows a more detailed investigation of the changes in ecosystem vulnerability to soil moisture and temperature throughout the course of the year for different land cover classes and subregions. In a wet regime, ecosystem activity is energy-limited, depending primarily on temperature and radiation, whereas in a transitional or wet system, soil moisture content is reduced and thus ecosystem activity is water-limited (Seneviratne et al., 2010; Zscheischler et al., 2015). From May to July, the Mediterranean is often vulnerable to hot and dry conditions, which is a typical feature of a soil moisture-limited regime (Seneviratne et al., 2010). Heat waves are a frequent characteristic of the Mediterranean summer (Conte et al., 2002) and are often connected to persistent anti-cyclonic regimes and droughts (Mueller and Seneviratne, 2012; Ulbrich et al., 2012). The vulnerability to dry conditions in autumn indicates that moisture reservoirs are often still depleted after the summer, impairing the onset of the next vegetation cycle. By contrast, plant growth is inhibited by too low temperatures in autumn, which distinguishes it from the antecedent summer period. The general transition to vulnerability to cold conditions already in August is astonishing. However, it should be noted that especially for the warmer regions – e.g. northwestern Africa, Turkey and the interior of Spain – either vulnerability to hot conditions prevails or no FAPAR anomalies are detected during this time (see Figs. 6 and B1), presumably because August is outside of the growing season. During the phase of the water-limited regime, soil moisture depletion in combination with high atmospheric evaporative demand leads to plant water stress and can ultimately cause plant mortality due to hydraulic failure or carbon starvation (van der Molen et al., 2011; Vicente-Serrano et al., 2020). As a coping strategy, plants e.g. reduce stomatal conductance to avoid hydraulic failure due to water loss by leaf transpiration, which consequently leads to reduced carbon uptake and thus decreased photosynthetic activity (van der Molen et al., 2011; Reichstein et al., 2013; Piao et al., 2019; Vicente-Serrano et al., 2020). The vulnerability to cold conditions in most months from November to April confirms that ecosystems are energy-limited in this period and is probably related to frost damage during cold spells. Related to the Cyprus Low, cold spells often co-occur with heavy precipitation in the eastern Mediterranean during this time (de Luca et al., 2020). Presumably, wet conditions only coincide with cold conditions, but are not damaging ecosystems as such. However, vulnerability of crops to wet conditions in winter was e.g. observed on the Iberian Peninsula in a study by Páscoa et al. (2017). While ecosystem activity in the northern Mediterranean is low during winter, this does not hold true for the southern Mediterranean – e.g. for some regions in Tunisia the NDVI peaks as early as December (Le Page and Zribi, 2019). Cloudiness during precipitation leads to reduced solar radiation and consequently lower surface temperature (Berg et al., 2015). This way,

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cold and wet conditions can lead to low transpiration rates of plants accompanied by low photosynthetic activity, leading to reduced extraction of soil moisture during that time period (Zscheischler et al., 2015). This highlights the bidirectional relation between vegetation and soil moisture, i.e. not only the state of the vegetation is dependent on soil moisture, but also vice versa. This mutual linkage is neglected in many studies (Dorigo et al., 2017).

Energy-limited regimes merge gradually into water-limited regimes from Scandinavia southwards to the Mediterranean in Europe (Teuling et al., 2009). Karnieli et al. (2019) investigated the relationship of the NDVI and land surface temperature at European scale, hypothesizing that a positive relationship indicates an energy-limited condition and a negative one a water-limited condition. Our results are mostly in agreement with the findings of their study that temperature and the NDVI are comprehensively negatively related in summer in Mediterranean Europe, whereas in spring this is only the case at the southernmost regions of Mediterranean Europe, while in other areas either neutral or negative relationships prevail. According to Le Page and Zribi (2019), temperature and the NDVI are always negatively correlated in northwestern Africa, while soil moisture and the NDVI are positively correlated. This indicates that this region is soil moisture-limited year-round, which is in good agreement with our results obtained using the ESA CCI soil moisture data set. However, the ERA5 Land soil moisture data set exhibits vulnerability to wet conditions in northwestern Africa in several months of the year, which might indicate lower suitability of this reanalysis data set to represent the soil moisture conditions in this region (see Figs. 6 and A2).

Extreme ecosystem impacts are not always connected to climatic extremes, but can also be caused by a combination of concurrent moderate climatic drivers (Pan et al., 2020; van der Wiel et al., 2020). Furthermore, extreme ecosystem impacts are not solely related to soil moisture and temperature anomalies. Other potential causes are e.g. windthrow, pest outbreaks and fires, which often exhibit synergistic effects in combination with droughts and heat waves (Gouveia et al., 2012; Reichstein et al., 2013; Batllori et al., 2017; Ruffault et al., 2018). Furthermore, many ecosystems are managed, which also affects ecosystem productivity (Smit et al., 2008). These additional drivers should be taken into consideration when interpreting the results of this study.

The impact of climate extremes on ecosystems depends highly on their timing (Smith, 2011; Wolf et al., 2016; Piao et al., 2019). Depending on the plant development stage, e.g. a heat wave can be either beneficial or detrimental (Hatfield and Prueger, 2015; von Buttlar et al., 2018; Piao et al., 2019). In the same way, droughts can either accelerate the phenological cycle or inhibit plant productivity and their impact on vegetation is strongly connected to the seasonal variations of the water balance (Spano et al., 2013; Gouveia et al., 2017). The highest detrimental impacts on ecosystems by droughts in the Mediterranean have been reported at the beginning of the year at the peak of the growing season (Ivits et al., 2016; Peña-Gallardo et al., 2019). The drought and heat wave in 2003 was comparably not that harmful to Mediterranean ecosystems, as it occurred in August, which is outside the main growing season (Ivits et al., 2016). The approach presented in this study helps to gain a better understanding of which stages of the year are vulnerable to which climatic condition. To our knowledge, none of the previous studies, which applied the framework for ecosystem vulnerability, accounted for the effects of seasonality so far. However, ecosystem responses are highly sensitive to the timing of events, therefore, it is crucial to consider this.

Climate change leads to seasonal shifts, which already becomes apparent in the strong phenological changes in the Mediterranean (Menzel et al., 2006; Gordo and Sanz, 2009, 2010). For example, higher temperatures lead to increased ecosystem

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productivity and subsequently higher evapotranspiration earlier in the growing season. Due to this, soil moisture is depleted faster and therefore more energy is transferred into sensible heat instead of latent heat. As a consequence of these hot and dry conditions, the growing season might end prematurely (Seneviratne et al., 2010; Lian et al., 2020). Our approach can potentially be used to detect how vulnerability at monthly scale within the year changes in future due to the alterations in climatic conditions and the phenological cycle. Hot and dry days are getting more persistent in summer, but droughts and warm spells are increasing in spring as well (de Luca et al., 2020; Vogel et al., 2021), which can have detrimental implications for the Mediterranean ecosystems as spring is the main growing season. With temperature increases in future, vulnerability to cold conditions might be constrained to a shorter time frame, whereas the time span with vulnerability to hot conditions might expand within the year. Increasing droughts are projected in the Mediterranean (Samaniego et al., 2018), while at the same time heavy precipitation events are projected to increase (Toreti and Naveau, 2015). Thus, it remains difficult to determine how vulnerability to dry and wet conditions will evolve in future.

4.2 Potential limitations of the methodological procedure

The presented method depends heavily on the quality of the employed data types for both the two drivers and the impact proxy. Several limitations regarding moisture data are well-known, e.g. the coarse spatial resolution impairs assessments at local scales. Furthermore, satellite-based soil moisture is limited to the retrieval of surface soil moisture, while deeper-reaching root-zone soil moisture is the actual ecologically relevant variable. Satellite-based soil moisture is only representative for the first five centimetres of the soil layer. The root zone of plants is usually deeper, which reduces the explanatory power of satellite-based soil moisture for drought impacts on ecosystems (Liu et al., 2016; Dorigo et al., 2017; West et al., 2019). Coupling of land surface models with satellite-based surface soil moisture could provide such information on root-zone soil moisture in future (Dorigo et al., 2017; Tramblay et al., 2020). Nevertheless, it should be noted that validations of the ESA CCI soil moisture data set with in situ observations from Mediterranean sites in Spain and France at depths from 5 to 30 cm showed high agreement (Albergel et al., 2013; Dorigo et al., 2015). The FAPAR is often assumed to be directly linked to productivity. However, droughts might lead to physiological changes such as stomata closure, which are not apparent in the spectral characteristics of the canopy and thus in the FAPAR but nevertheless invoke a decreased productivity. This was e.g. the case in forest ecosystems during the drought and heat wave event in 2003 in Europe (Reichstein et al., 2007; Zhang et al., 2016).

The Mediterranean Basin is characterised by large spatial variability because of its complex topography (Lionello et al., 2006). The relatively coarse resolution of the ESA CCI soil moisture data set is currently limiting the representation of this high spatial complexity (Crocetti et al., 2020). Many land cover classes express similar patterns over the course of the year according to our results. This could potentially indicate that pixels are sometimes not homogeneous enough, but rather represent a mixture of several land cover classes due to the coarse resolution of 0.25 °.

Many studies do not consider lagged effects in their design and the choice of a suitable time scale to account for such effects is not trivial and under debate (Zeng et al., 2013; Ivits et al., 2016). Response time varies depending on the type of event and the affected ecosystem. The response lag of vegetation is land cover-specific, as plants have various regulatory physiological

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functions to react to changes in soil moisture such as stress memory, water storage and stabilisation activities at the community level (van der Molen et al., 2011; Niu et al., 2014; Zhang et al., 2017). Faster response times to droughts are observed for pasture and crops compared to shrubs and forests (Chen et al., 2014; Bachmair et al., 2018). Generally, responses to drought are slower in semi-arid and sub-humid biomes compared to arid biomes (Vicente-Serrano et al., 2013). A study by Ivits et al. (2016) at European scale found that vegetation in the Mediterranean responds slowly to meteorological droughts compared to most other European regions. Impacts on vegetation by meteorological and soil moisture droughts are often largest within the preceding one to two months (Zeng et al., 2013; Chen et al., 2014; Wu et al., 2015; Papagiannopoulou et al., 2017; Bachmair et al., 2018), which is the reason we decided on a three-month time scale in the moving average applied to the environmental drivers in our approach. Temperature responses are usually faster than responses to drought, but can still exhibit lagged responses up to a few months (Zeng et al., 2013; Papagiannopoulou et al., 2017). Temperature and soil moisture anomalies are usually analysed on different time scales (typically on a daily scale for temperature and on a monthly scale for soil moisture), which renders their joint assessment difficult. Ecosystem impacts can also vary substantially on a temporal scale from e.g. temporary changes in productivity to persistent regime shifts (Crausbay et al., 2017). Therefore, using a single time scale might not capture all relevant temporal dynamics. The choice of the optimal time scale is non-trivial and e.g. time scales of less than a month for investigating drought impacts on vegetation have also been suggested (West et al., 2019).

Our analysis is year-round without being explicitly restricted to the months of the growing season, which makes it easily transferable to any study area. We decided this for two reasons. First, it is complex to account only for the months of the growing season, as there is a large variability depending on latitude and longitude within the Mediterranean Basin (Lionello et al., 2006). Second, the analysis is implicitly limited to the growing season, because FAPAR deviations during the dormant season are expected to be small and thus will exceed the extremeness threshold only on rare occasions. In our study, it can be clearly noted that the number of detected events is not distributed equally throughout the course of the year. They are at a minimum at the transition from summer to autumn when ecosystem activity is low in the Mediterranean (see section 3.2). Therefore, large areas – especially in the interior of the countries – are under-represented in these months. Results for months during the dormant season should be interpreted cautiously (Ivits et al., 2016), taking into account that they depend on a considerably lower number of events. These events might be representative solely for specific ecosystems that are still active at this time of the year or may partially result from noise in the data.

5 Conclusions

The seasonal ecosystem vulnerability analysis presented in this study helps identify at which time of the year vulnerability to a certain climatic condition occurs. The vulnerability of Mediterranean ecosystems to the concurrent climatic drivers temperature and soil moisture was successfully assessed using the FAPAR as a proxy for ecosystem productivity, with a focus on the variation of impacts with seasonality. Our results are in line with the characteristic intra-annual change between an energy-limited and a water-limited regime from winter to summer in the Mediterranean (Schwingshackl et al., 2017). In general, three seasonal stages of vulnerability are identified throughout the year: 1) vulnerability to hot and dry conditions in late spring to

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midsummer, 2) vulnerability to cold and dry conditions from the end of summer to mid-autumn and 3) vulnerability during cold and wet conditions from the end of autumn to mid-spring. There are several regions which deviate from this pattern, e.g. the hot and dry regime is extended from spring to autumn in Turkey, whereas the Balkan Peninsula is continuously energy-limited throughout the year and not vulnerable to hot conditions. Our results point out the necessity to incorporate seasonality in the vulnerability analysis concept, as well as to examine vulnerability at a subregional scale to account for the large spatial and temporal variability in the Mediterranean. Increasing aridity and fast changes in the phenological cycle are observed in the Mediterranean Basin due to climate change (Gao and Giorgi, 2008; Gordo and Sanz, 2010). The approach for detecting seasonal ecosystem vulnerability opens novel opportunities for developing early-warning tools to identify detrimental ecosystem conditions, water limitations and irrigation demand in near real time and for performing long-term assessments of ecosystem vulnerability and change for the near- and mid-future climate scenarios.

Code and data availability. The code can be retrieved from https://gitup.uni-potsdam.de/joschavogel/ecosystem_vulnerability. All data sets used in this study are publicly available.

Appendix A: Comparison of ecosystem vulnerability using soil moisture from ESA CCI and ERA5 Land

The ERA5 Land data set gives very similar results compared to the ESA CCI data set in the second half of the year (August–December) for most land cover classes (see Fig. A1), where the patterns are identical in most cases – for "All land cover classes" they are in agreement from June to December. However, in spring they often deviate, e.g. in May where dry conditions arise in the ERA5 Land data set, whereas using ESA CCI there is no significant vulnerability to dry conditions for many land cover classes. "Sparse vegetation" is often prone to dry conditions in the second half of the year in the ESA CCI data set, whereas according to the ERA5 Land data set it is not. Also "Forest (broadleaved)" and "Forest (needleleaved)" are prone to dry conditions from June to September in the ESA CCI data set, unlike in the ERA5 Land data set where they are mostly either vulnerable to wet conditions or not vulnerable to soil moisture at all. However, there is no apparent systematic bias over all classes, rather it changes by month. So, in February, vulnerability in the ERA5 Land data set is e.g. leaning more towards dry conditions, whereas in July this pattern is reversed.

During most of the year, the majority of subregions coincide well in both data sets, but there are exceptions (see Fig. A2). There is vulnerability to dry conditions in August in the Balkan, the Iberian Peninsula and northwestern Africa for ESA CCI soil moisture, whereas for ERA5 Land this is reversed or insignificant. For northwestern Africa, ERA5 detects lower vulnerability to dry conditions than ESA CCI throughout the course of the year. In addition, in the Iberian Peninsula vulnerability to wet conditions is pronounced at the beginning of the year for ESA CCI, whereas for ERA5 Land most months during this period show vulnerability to dry conditions.

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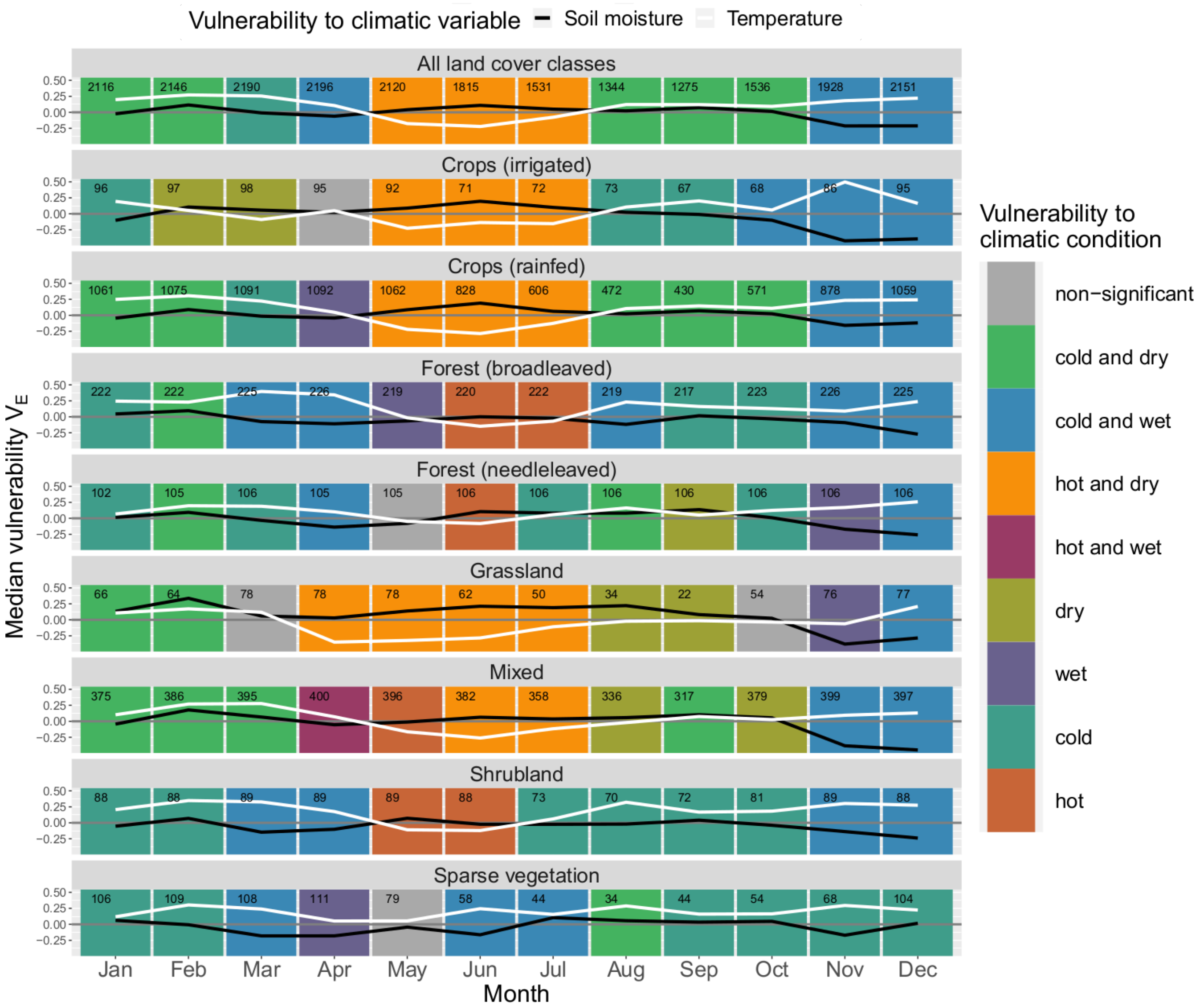

Figure A1. Median monthly ecosystem vulnerability per land cover. Vulnerability to temperature (ERA5 Land) is shown in white and vulnerability to soil moisture (ERA5 Land) is shown in black for each month of the year (columns) for each land cover (rows). Months with statistically significant deviation of climatic drivers during non-hazardous and hazardous ecosystems conditions according to the Mann-Whitney U test based on a significance level $\alpha = 0.05$ are shown in colour (see legend), all other months are shown in grey. The number of pixels in which an event has occurred in this month and land cover within the period 1999-2019 is shown in the upper left corner of each panel.

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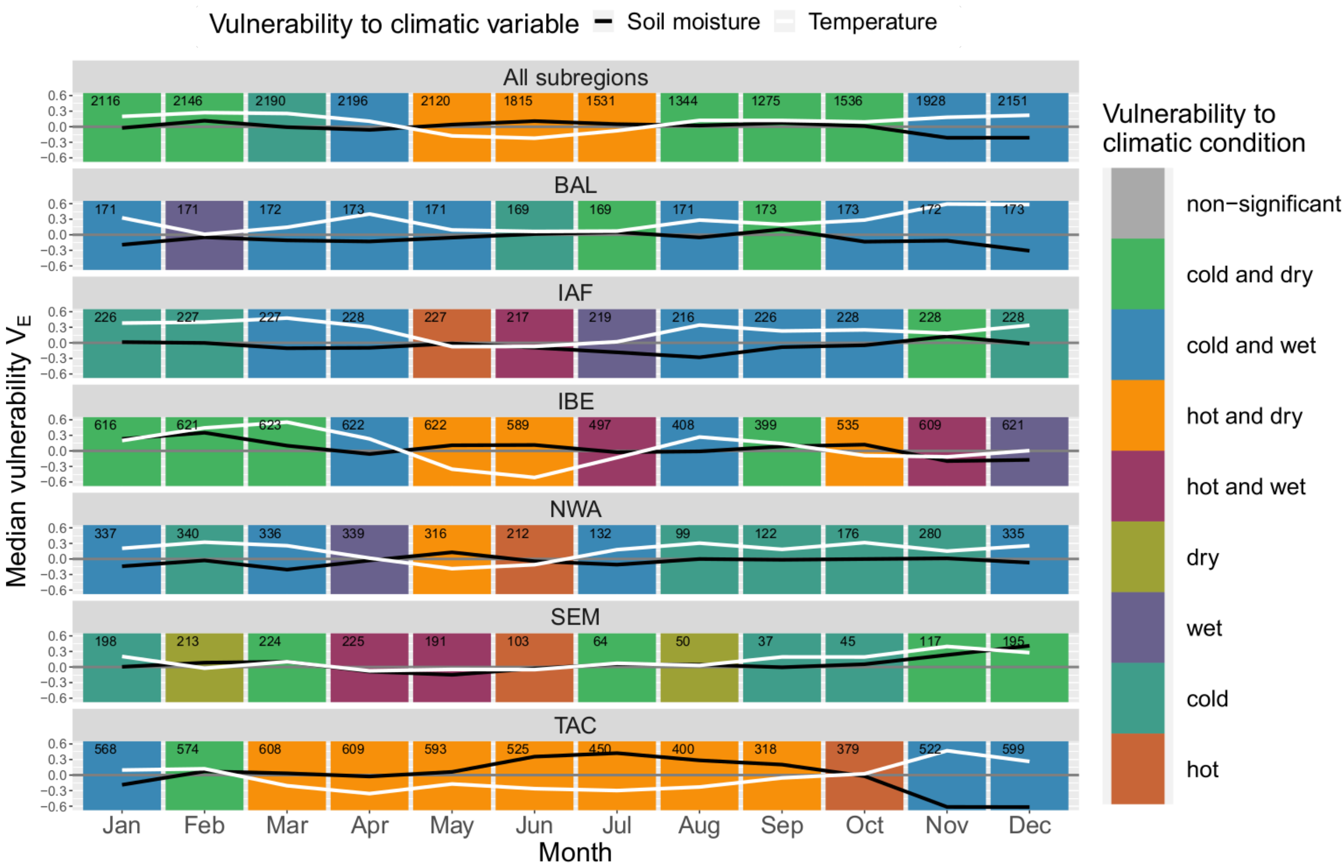

Figure A2. Median monthly ecosystem vulnerability per subregion. Vulnerability to temperature (ERA5 Land) is shown in white and vulnerability to soil moisture (ERA5 Land) is shown in black for each month of the year (columns) for each land cover (rows). Months with statistically significant deviation of climatic drivers during non-hazardous and hazardous ecosystems conditions according to the Mann-Whitney U test based on a significance level $\alpha = 0.05$ are shown in colour (see legend), all other months are shown in grey. The number of pixels in which an event has occurred in this month and land cover within the period 1999-2019 is shown in the upper left corner of each panel.

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Appendix B: Further materials

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Table B1. Overview of the land cover classes aggregation.

Number	Original class	Aggregated class
10	Cropland, rainfed	Crops (rainfed)
11	Cropland, rainfed, herbaceous cover	
12	Cropland, rainfed, tree or shrub cover	
20	Cropland, irrigated or postflooding	Crops (irrigated)
30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	Mixed
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	
100	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	
60	Tree cover, broadleaved, deciduous, closed to open (>15%)	Forest (broadleaved)
62	Tree cover, broadleaved, deciduous, open (15-40%)	
70	Tree cover, needleleaved, evergreen, closed to open (>15%)	Forest (needleleaved)
120	Shrubland	Shrubland
130	Grassland	Grassland
150	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	Sparse vegetation
153	Sparse herbaceous cover (<15%)	
200	Bare areas	
190	Urban areas	None (Omitted)
210	Water bodies	None (Omitted)

Table B2. Overview of the six subregions and the corresponding countries used in this study

Short Name	Long Name	Countries
IBE	Iberian Peninsula	Portugal, Spain
IAF	Italy and France	France, Italy
BAL	Balkan Peninsula	Albania, Bosnia and Herzegovina, Bulgaria Croatia, Greece, North Macedonia, Montenegro
TAC	Turkey and Cyprus	Cyprus, Turkey
SEM	Southeastern Mediterranean	Iran, Iraq, Israel and Palestinian territories Jordan, Lebanon, Libya, Syria
NWA	Northwestern Africa	Algeria, Morocco, Tunesia

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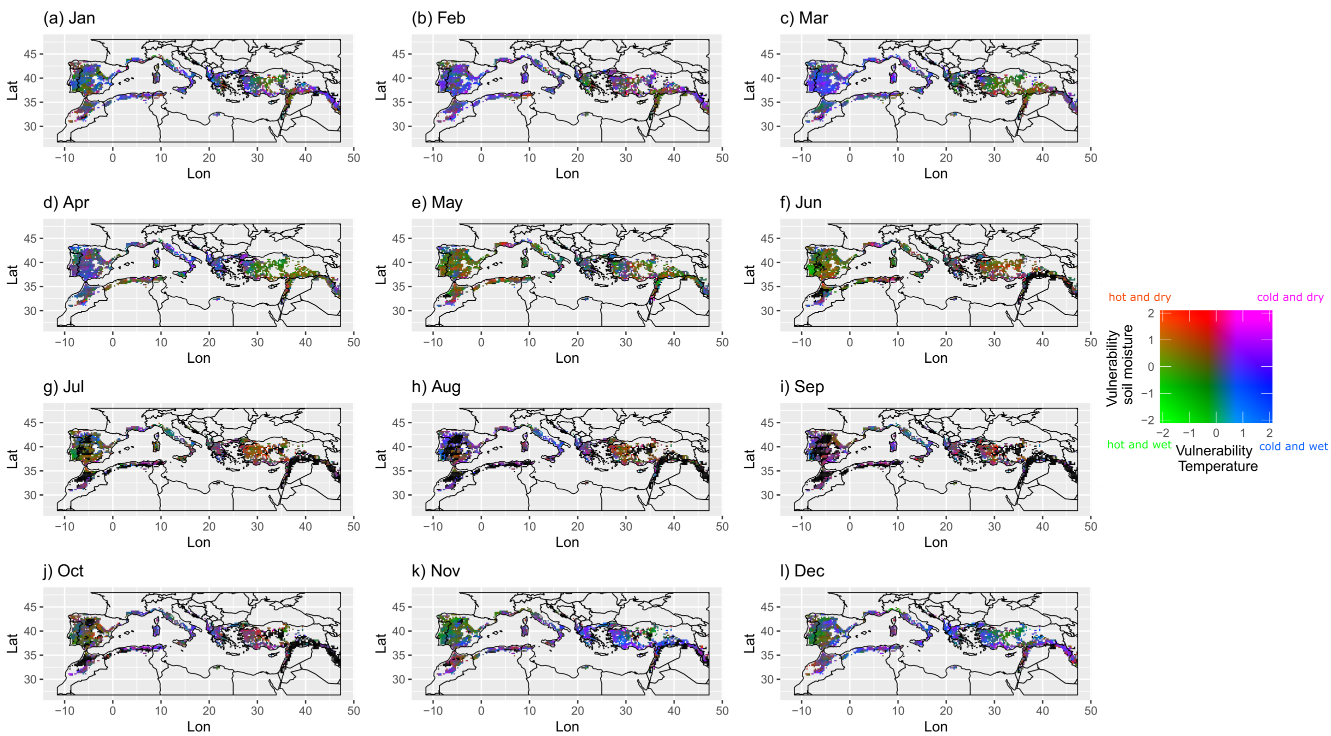

Figure B1. Average monthly vulnerability to soil moisture (ESA CCI) and temperature (ERA5 Land) in the Mediterranean Basin for (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November and (l) December. Pixels without any events during the respective month are displayed black.

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Author contributions. JV, EP and VA designed the study and the methodology. JV developed the computer code, performed the analysis and visualised the results. EP supervised the research project. JV wrote the original draft with contributions from all co-authors.

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

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