# Mediterranean Badlands: their driving processes and climate change futures

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## Abstract

Badlands are landforms that occur all over the World. In the Mediterranean region, badlands are found in both dry (arid and semiarid) and wet (subhumid and humid) environments, and are characterized by complex hydro-geomorphological dynamics, high intense erosion processes and extreme sediment yield. Understanding the impact of Global Change is key to predict the on-site and off-site effects on badland dynamics, particularly its consequences on bedrock weathering, on sediment yield and delivery and on plant colonization. Here, conducting a systematic literature review, we analyzed an extensive database and identified the main climate-drivers affecting the hydro-geomorphological dynamics in Mediterranean badlands (based on Non-Metric MultiDimensional Scaling and Structural Equation Modelling analysis). Later, we examined the main impacts expected from climate change forecasting in the near future, and we explored the interactions between badlands response to climate variation. In Mediterranean badlands, weathering processes are mainly related to wetting-drying cycles and freeze-thaw cycles in dry and wet badlands, respectively. In both environments, rainfall amount appears as the main driver for runoff response, and rainfall amount and rainfall intensity for erosion dynamics. Future climate scenarios forecast a decrease in annual rainfall, number of rainfall events and frost days, and in soil moisture, and an increase in rainfall intensity. These changes will have direct hydro-geomorphological implications with direct and indirect effects on badland dynamics. This may result in a decrease in annual runoff in dry badlands, but the occurrence of more frequent extreme events would increase soil erosion and could negatively affect biological soil crust. In wet badlands, weathering and erosion processes may decrease, and a stabilization of the slopes, with consequently improved vegetation growth, may be expected. In addition, the forecasted changes must be taken into account, especially considering the possible off-site effects of these extreme environments.

**Keywords**: badlands, Global Change, climate change, weathering, erosion, hydrology

## 1. Introduction

Badlands have been defined by different criteria in the last decades (i.e. Bryan and Yair, 1982; Fairbridge, 1968; Gallart *et al.*, 2002; Torri *et al.*, 2013). Most definitions agreed that badlands are landforms developed on soft or poorly consolidated bedrock with limited plant cover, where a wide range of geomorphic processes play a paramount role, including weathering and erosion (Martínez-Murillo and Nadal-Romero, 2018). Badlands develop in a large variety of climatic regions and on a relatively wide range of lithologies. Nevertheless, the geomorphic processes contributing to badland evolution show a large spatial and temporal variability, in spite of which badlands tend to produce converging geoforms (Kasanin-Grubin and Bryan, 2007). The particular topographic and lithologic conditions, as well as the rapid changes these systems undergo in short periods of time and the changes observed in the surrounding areas (i.e. abandonment of grazing activities), result in badlands with a huge interest from a geomorphological, ecological, educational, economic and social point of view. All these attributes make badlands excellent research laboratories for the study of hydro-geomorphological processes at an affordable human scale, and particularly make these systems especially interesting to study processes involved in Global Change (Nadal-Romero and García-Ruiz, 2018).

From a geomorphological point of view, the hydrological and erosion responses are extremes, especially in subhumid and humid badlands, showing important on-site and off-site implications. The occurrence of high erosion rates modifies the physical properties of the regolith, causes a loss of nutrients and destabilizes the hillslopes hindering plant colonization (Cantón *et al.*, 2018). Moreover, water and sediment fluxes, originated in badland areas during rainstorms, very often provoke severe environmental and economic off-site effects, such as channel silting, sediment accumulation in the alluvial plain, reservoir sedimentation (Copard *et al.*, 2018), reducing the quality of water for domestic and industrial uses, which in turn may produce important economic impacts (Pimentel *et al.*, 1995).

From an ecological perspective, the extreme environmental conditions of badlands, (e.g. the high slope gradients and instability) configure a high variety of microclimatic conditions (Rodríguez-Caballero *et al.*, 2019), which contribute to a high biodiversity and the presence of frequent endemic species (Torri *et al.*, 2018).

They are also relevant from a social and economic point of view. Badlands can be considered aesthetic landscapes, and also magnificent scientific, touristic and educational laboratories for runoff, erosion and vegetation studies at accessible spatial and temporal scales, and for these reasons many researchers suggest that they deserve to be protected (Zgłobicki *et al*., 2019). Indeed, some badland areas are included within conservation figures such as National Parks or Nature Reserves, and often attract visitors and activities in nature (Torri *et al*., 2013; Zgłobicki *et al*., 2019). Such activities raise the value of badland areas and encourage local communities to contribute in the preservation of these landscapes.

Thereby, research related to badlands has increased progressively throughout the last decades, particularly in the Mediterranean region (Gallart *et al*., 2013a; Martínez-Murillo and Nadal-Romero, 2018). However, most of these badlands studies have been mainly focused on explaining past and present processes, while the changes expected under future climatic conditions have been hardly analyzed, and present contradictory results.

Most of the climate models forecast an increase in temperature and changes in rainfall patterns by the end of the 21st century (Lionello and Scarascia, 2018). However, there is no information about the magnitude and directions of hydro-geomorphological changes in badlands. This lack of knowledge is due to the high uncertainty of the main climatic predictions (Lionello *et al*., 2014; Vicente-Serrano *et al*., 2020), and the insufficient information about the main climate-drivers controlling the badlands hydro-geomorphological response, and how the effects of these drivers change, as climate does. Changes in temperature and precipitation can critically affect weathering processes, regolith evolution and soil development, hydrological and erosion dynamics, sediment transfer from badland areas to river catchments, and vegetation dynamics. As these processes are interrelated, climate-drivers affecting one of them may have indirect impacts on the others. For example, any climate change that promotes weathering may favor infiltration and would probably increase sediment availability. Thus, it is often difficult to disentangle the direct and independent effects of a climatic driver on a specific hydro-geomorphological process, and the interactions among this process and others also affected by climatic drivers. Structural Equations Models (SEMs) allow us to analyze the complex relationships among different climatic drivers and hydro-geomorphological processes and to separate the direct and indirect effects of these drivers (e.g. Chamizo *et al*., 2012, 2017; Rodriguez-Caballero *et al*., 2013, 2014). This provides a more comprehensive picture of the relative importance of these drivers yielding insights into the mechanisms behind their effects and may be very useful in order to understand the magnitude and directions of future hydro-geomorphological changes in badlands, and the resulting on-site and off-site effects in response to changing climatic conditions.

One of the regions of the world more prone to suffer intensely the effects of Global Change is the Mediterranean region. Numerous climate studies confirm changes in surface temperature and rainfall patterns (increase in drought frequency and rainfall intensity) (González-Hidalgo *et al*., 2020; Vicente-Serrano *et al*., 2020). Besides, this region has a long history of human activity and is densely populated, resulting in land degradation and land cover changes. Thereby, it is expected that the consequences of Global Change will be magnified in this region (Lionello and Scarascia, 2018), causing measurable local impacts with potential regional consequences.

Badlands develop within a wide range of climatic environments, especially in the Mediterranean region (Nadal-Romero *et al*., 2011). The study of badland areas in the Mediterranean region supposes a challenge (numerous complex feedbacks) and an essential target. Mediterranean badlands are subject to dramatic changes that will affect the hydro-geomorphological and vegetation dynamics at different spatial and temporal time-scales (Nadal-Romero *et al*., 2018a; Rodríguez-Caballero *et al*., 2014). Nevertheless, most of the studies published on Mediterranean badland areas have insufficient temporal length to predict the impacts of Global Change. Despite this is the largest challenge facing future landscapes, there are no prospective analysis on its effects in Mediterranean badlands. This paper aims to gain more insight into the discussion by exploring the following critical research question: What is the fate of Mediterranean badlands under a context of Global Change? To answer it, this study aims at (i) identifying the main climate-drivers affecting the hydro-geomorphological dynamics in a range of climatic environments where Mediterranean badlands develop (from arid to humid areas), and (ii) analyzing how they will change in the future and the likely response of these extraordinary landscapes to Global Change.

## 2. Material and Methods

### *2.1. The Mediterranean region*

The Mediterranean region comprises a heterogeneous area around the Mediterranean Sea that stretches c.3,800 km east to west from the tip of Portugal to the shores of Lebanon, and c.1,000 km north to south from Italy to Morocco and Libya (European Commission, 2009), thus encompassing territories from Europe, Africa and Asia. Overall, it is affected by a Mediterranean climate with mild wet winters and warm and hot dry summers. Nonetheless, this general description of the climatic characteristics covers up significant differences, well explained by the heterogeneity of the region itself. Geographical location, orography, humidity and heat supplied by the Mediterranean Sea, are all relevant traits that determine local climatic gradients.

Badlands are distributed along the wide variety of climatic conditions that characterize the Mediterranean region. In this study, we use the climatic classification of badlands proposed by Gallart *et al*. (2002), with some small changes, reducing the groups of homogeneous badland types from three to two, due to the scarcity of available data from arid badlands: (i) arid and semiarid (hereafter dry badlands), and (ii) subhumid and humid badlands (hereafter wet badlands).

Dry badlands are developed in dryland areas with mean annual rainfall below 700 mm. This group includes examples of arid badlands located in the Zin Valley (northern Negev, Israel), characterized for being old landscapes apparently stabilized (mainly by biocrusts) under present climate conditions (Yair *et al*., 2011, 2013) to more active systems, such as Tabernas (Spain) and Basilicata badlands (Italy) (e.g. Brandolini *et al*., 2018; Calvo and Harvey, 1996; Cantón *et al*., 2001a, 2001b, 2003; Rodríguez-Caballero *et al*., 2014, 2018a).

Wet badlands are very often developed in mountain areas, with mean annual rainfall over 700 mm. They are characterized by extreme hydro-geomorphological dynamics and very high erosion and sediment yields. Some of the best examples are located in the Pyrenees (Spain) (e.g. Gallart *et al*., 2013b; Llena *et al*., 2020; Nadal-Romero *et al*., 2018a) and the sub-Mediterranean Alps (France) (e.g. Mathys *et al*., 2003).

### ***2.2. Data collection and analysis***

#### *2.2.1. Exploring the Mediterranean badlands response along climatic gradients*

In a first stage, we performed an exploratory analysis related to the main climate variables (annual rainfall and mean annual temperature) and sediment yield in badland areas, based on the database created by Nadal-Romero *et al.* (2011, 2014). This database included 55 references from 87 study sites including data collected from Morocco, Spain, France, Italy, Albania, Greece, Turkey and Israel. All these studies have information on sediment yield under natural rainfall with a measuring period of at least one year. In addition, in the case of catchments >10ha (considered large in this study), they were only selected when badlands occupied at least 5% of the total catchment.

*2.2.2. Analysis of climate-drivers in Mediterranean badland areas*

In order to achieve the objective of this manuscript (identifying the main climate-drivers affecting the hydro-geomorphological dynamics in badland areas) the database described by Nadal Romero *et al*. (2011 and 2014) was screened and updated as follows. The study scope was focused on climate factors controlling badlands hydro-geomorphological response from the Mediterranean region. By reading the abstracts and a main body skim reading, the database was screened to identify only relevant studies that described the main climate-drivers controlling badland hydro-geomorphological response (12 manuscripts from the original database) at the catchment scale. Then, a second literature search was performed in Scopus on February 2020 following a systematic literature process according to the guidelines proposed by Mengist *et al*. (2020) as the framework of Search, Appraisal, Synthesis and Analysis (SALSA) (Booth *et al*., 2012). This new search was restricted to studies published up to 2019, using as key words “Badlands”, “catchment”, and all possible combinations of keywords for hydro-geomorphological response (i.e. [sediment yield, erosion, runoff or weathering]) OR Global Change (i.e. [climate change or Global Change]). We obtained a new set of records to be considered (129 studies). After application of the screening process previously described, 32 studies fulfilled all the inclusion criteria (these were added to the previous database leading to a final database of 44 studies, see Supplementary Table S1).

Later, the synthesis stage consisted of extraction and classification of relevant information to identify the main climate-drivers affecting the hydro-geomorphological dynamics of badlands. For each study in the database (see synthesis in Table S1 Supplementary Material), the following information was collected (when available): reference, measurement location, climate characteristics (mean annual rainfall and temperature), and main climate-drivers that conditioned the hydro-geomorphological processes (Table 1). For the data analysis stage, we built a driver binary matrix indicating presence or absence of each single driver per study site. From this, we calculated the total number of studies where each driver was reported to have an effect on each study process (weathering, hydrology and erosion). We estimated the relative importance of the different drivers on each single process, as the ratio of the number of studies in which each single driver was reported to the total number of reports for the whole set of drivers. This was done for each single analyzed process, and considering the complete dataset of for dry and wet badlands separately (See Table S1, Supplementary material). Finally, we performed a Non-Metric MultiDimensional Scaling (NMDS) to compare the main drivers acting on each study case within the database.

Analysis was performed using the vegan package (Oksanen *et al*., 2013) in R (R Core Team, 2013). Runs were based on jaccard dissimilarity that well suited to deal with presence-absence binary data. Finally, nonparametric Spearman rank correlations were performed between NMDS axis values and environmental variables to determine how climate-drivers affecting badlands response vary along the temperature and precipitation gradient in which Mediterranean badlands develop.

*2.2.3. Analysis of climate-drivers and hydro-geomorphological dynamics interactions based on field studies: El Cautivo and Araguás catchments*

Weathering, runoff and erosion are interrelated processes, and climate-drivers affecting one of these processes may have indirect impacts on the others. Exploratory analyses based on Structural Equation Models (SEMs) represent a suitable tool to analyse the dependence of one variable on another, as they represent multiple path relationships, and separate direct and indirect effects between predictors. Application of SEMs has shown successful results in a number of hydro-geomorphological studies (e.g. Chamizo *et al*., 2012, 2017; Rodríguez-Caballero *et al*., 2013, 2014). Thus, we built a SEM to provide integrated knowledge on the major climatic drivers of badlands hydro-geomorphological response, partitioning causal influences among several variables, and identifying direct and indirect effects of the drivers. This analysis demonstrates how well data support a set of hypothesized direct and indirect relationships among the variables by comparing the covariance structures of model and observed data (Mitchell, 1992; Iriondo *et al*., 2003; Grace *et al*., 2010). We hypothesized a priori model based on well-established causal relationships already identified during the review process (Supplementary Figure 1). Model included hydro-geomorphological variables (i.e. runoff rate [RR], runoff coefficient [RC] and maximum peak flows [Qmax] and sediment yield [SY]), and the main climate-drivers (rainfall amount [R], maximum rainfall intensity in 5 min [I5max], 3-days antecedent rainfall [$R_{-3\ days}$], and the number of wetting-drying [W-D] and freezing cycles 10 days previous to the event [Fdc] in dry and wet areas, respectively) (see Supplementary Figure 1). As records of these variables in a high number of events was not available for all the study sites included in our database, we restricted the application of the SEM to two study sites, for which long-term event records was available. Thus, this general model was separately tested in two experimental catchments representative of the two groups of Mediterranean badlands, using a high number of stormflow events recorded on each catchment. The two catchments representative of dry and wet badlands were respectively: El Cautivo (number of events: 127) and Araguás (number of events: 139) (Cantón *et al*., 2001a, 2001b; Rodríguez-Caballero *et al*., 2014; Nadal-Romero *et al*., 2018a). El Cautivo (Tabernas badlands) is located in SE Spain. The climate is semiarid type, with an average annual temperature of 17.8 ºC and an average annual rainfall of 235 mm (for more information see Cantón *et al*., 2001b, 2003 and Rodríguez-Caballero *et al*., 2014, 2018a). Runoff and erosion has been measured at this site since 1990 with a H-type flume located at the catchment outlet, which had a contributing area of 1.8 ha. Data corresponding to a period of 20 years was used for running the SEM at this site. The Araguás catchment (45 ha) is located in the Central-Western Pyrenees (NE Spain). The climate is of sub-Mediterranean mountain type, with an average annual temperature of 10 ºC and an average annual rainfall of 800 mm (for more information see Nadal-Romero and Regüés, 2010). Data correspond to a period of 14 years was used for running the SEM at this site.

Goodness of fit between the empirical and the model-implied covariance matrix was assessed by $\chi^2$, the Goodness of Fit Index (GFI), the Non-Normed Fit index (NNFI) and the Root Mean Square Error (RMSE). Significant $\chi^2$ values indicate the model does not fit the data, whereas values of GFI and NNFI over 0.9 and RMSE below

0.05 indicated the model is good. Finally, we analyzed differences in the climate-drivers controlling hydro-geomorphological response of dry and wet badlands by comparing individual path coefficients between variables obtained with the two different datasets. SEM analysis was done using SPSS AMOS 18 software (AMOS Development Corp., Mount Pleasant, South Carolina, USA).

### *2.3. Projected climate change scenarios*

Based on climate forecasts obtained by the fifth phase Climate Model Inter-Comparison Project (CMIP5), we analyzed expected trends in the main climate-drivers governing the Mediterranean badland dynamics identified in the literature revision and by the SEM analysis. To do this, we obtained information of: (i) mean annual rainfall; (ii) the simple daily intensity index (SDII; Brunetti *et al*., 2001); (iii) days with rainfall > 1 mm (as a proxy of the number of precipitation events); (iv) number of frost days (defined as the total number of days per year with absolute minimum temperature below 0°C); and (v) water content of the soil layer. The relative change on each driver by the year 2050 (period between 2035 and 2065) relative to historical values (period between 1986 – 2005) was obtained, for the four different representative concentration pathways (RCPs) defined in the CMIP5 (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). Mean daily precipitation and soil moisture content were calculated using the full set of general circulation models considered for the CMIP5 and climate indices (days with rainfall > 1 mm, SDII and the number of frost days) were calculated using the full set of general circulation models considered in the ETCCDI extremes indices archive (Peterson, 2005). All climate predictions were obtained from the KNMI Climate Explorer (https://climexp.knmi.nl). Finally, values of specific climate predictions for each study site described in Table S1 was extracted, and this information was used to elucidate the future response of the different badland types.

## 3. Results and Discussion

### *3.1.* ***Climate-drivers in badland areas***

Badland hydro-geomorphological functioning has aroused much concern for more than 100 years (Nadal-Romero *et al*., 2018b). As a result, the main drivers governing badlands response have been identified in different locations around the world (i.e. Boardman *et al*., 2015; Bollati *et al*., 2019; Clarke and Rendell, 2010; Yang *et al*., 2019). However, up to now, available datasets did not allow us to analyze how these drivers have varied in response to climate changes and their impacts on badlands hydro-geomorphology, as most of them cover only short periods of time. An extensive literature revision showing badlands erosion rates and the main climate-drivers controlling them, along a climatic gradient, has allowed us to partially filling this gap. As observed in Supplementary Figure 2, erosion rates increased as mean annual rainfall did. Thus, SY was more than 10-fold higher in humid and cold badlands than in arid and semiarid ones. No significant differences have been found between arid and semiarid badlands. These results support our initial classification of Mediterranean badland sites according to the precipitation regime into two main classes: dry badlands and wet badlands. The data also showed a high variability.

Differences in SY between dry and wet Mediterranean badlands have been traditionally related to differences in rainfall regime (Gallart *et al*., 2013a). However, our literature review reveals other important climate-drivers governing the Mediterranean badlands functioning with different relevance in each climatic region (Figure 1; Supplementary Table S1). Figure 1a shows the NMDS ordination of the main climate-drivers for the different analyzed hydro-geomorphological processes (weathering, hydrology or erosion) from the Mediterranean badlands with available data. The study cases appear aligned along a gradient of increasing annual rainfall and decreasing annual temperature, from the lower left side of the plot that included dry badland sites, towards the upper right side of the plot, where wet badlands are located. In addition, the NMDS graph illustrated a clear cluster of the climate-driving factors. Wet badlands tended to group on the upper part of the two-axis plot, associated to drivers such as presence of snow, antecedent moisture, freeze-thaw cycles and total rainfall amount. In contrast, dry badlands grouped at the lower part of the plot being more influenced by rainfall intensity, and timing and seasonality.

A deeper analysis of the relative frequency of climatic factors identified as drivers for the main operating processes (weathering, hydrology and erosion) corroborated this overall trend. However, as observed in Figure 1b, the relative importance of the different climatic variables varies depending on the analyzed process and climatic region.

(i) In **dry** Mediterranean badlands, the main climate-driver is rainfall (magnitude, intensity, and temporal rainfall distribution), although the different studies present some singularities. Wetting-drying cycles appear as the main control for weathering in dry badlands (Figure 1b), triggering physical, chemical and mineralogical changes in the parent material, whose intensity depends on material properties, for instance gypsum, sodium or swelling clay contents (Calvo and Harvey, 1996; Piccarreta *et al*., 2006a; Desir and Marín, 2007, 2013). Although a few wetting-drying cycles are sufficient to induce mineral dissolution, the increase in the number of cycles has been demonstrated to boost weathering processes (Cantón *et al*., 2001a; Pulice *et* *al*., 2013). In fact, an increase in weathering rates proportional to the number of rainfall events has been described (Cantón *et al*., 2001a). Apart from the number of rainfall events, the rainfall amount and the temporal distribution are also important drivers for weathering, modulating the intensity of weathering processes: the higher the rainfall amount, the deeper the physical-chemical-mineralogical alterations (Pulice *et al*., 2013).

Rainfall amount and rainfall intensity are identified as the paramount drivers of runoff generation (Figure 1b). Kuhn *et al*. (2004) and Yair *et al*. (2013) indicated that in arid badlands (Zin Valley), the duration of runoff-effective rainfalls is of critical importance to understand the hydrological dynamics, and only short high intensity rainfalls are effective. These authors suggested that more important than total rainfall is the frequency of individual rainfalls with magnitude sufficient to generate continuous runoff, erosion and sediment export. In general, rainfall thresholds for runoff generation are low, with reported values of 6 mm (Desir and Marín, 2007), 9 mm (Cantón *et al*., 2001b), 10 mm (Picaretta *et al*., 2006) or 11 mm (Sirvent *et al*., 1997) for different dry badlands. Nonetheless, rainfall to runoff is highly variable in each site depending on the rainfall intensity and moisture antecedent conditions (Cantón *et al*., 2018). As it is revised in different studies (i.e. Cantón *et al*., 2018) traditionally runoff generation in badland areas was related to infiltration excess surface runoff (related to rainfall variables), but there are other interacting drivers (such as antecedent moisture content), that may influence runoff generation as well, suggesting that other processes (such as saturation excess) due to partial saturation of the soil profile may operate in badland areas.

Likewise, both the rainfall amount and intensity also govern the erosion response of dry badlands (Figure 1b) as demonstrated several authors in Tabernas (southeastern Spain), Las Bardenas (northern Spain), and Basilicata and Sicily, (southern Italy) badlands (Brandolini *et al*., 2018; Calvo-Cases and Harvey, 1996; Cantón *et al*., 2001b; Desir and Marín, 2013). The rain/drought sequences have also been pointed as a relevant factor affecting geomorphological dynamics, as a consequence of the mentioned influence on weathering processes and consequently on sediment availability (Calvo-Cases and Harvey, 1996), sometimes expressed as the maximum number of consecutive dry and wet days or the mean dry and wet spell days (Piccarreta *et al*., 2006a). Other studies found that not only was the rainfall intensity a controlling factor on erosion but also the rainfall temporal distribution: soil erosion is mainly triggered during long-lasting dry periods with low-frequency heavy rainfalls (Brandolini *et al*., 2018). Even though in dry badlands runoff and erosion responses are much more driven by rainfall amount and intensity than by antecedent moisture (Khun *et al*., 2004; Martínez-Murillo *et al*., 2013; Yair *et al*., 1980), the effect of this variable can be appreciated at detailed timing (Cantón *et al*., 2001b). In addition, antecedent moisture may affect hydraulic gradient at the start of the rainfall event, affecting sealing and hydrocompaction processes.

(ii) In **wet areas**, weathering processes are mainly related to freeze-thaw cycles (frost growing, water availability and cold temperatures in winter) and snow falls and melting, whereas hydrological dynamics are mainly related to total rainfall amount, and erosion dynamics related to rainfall amount and rainfall intensity (Figure 1b).

Llena *et al*. (2020) showed that regolith cohesion is significantly correlated with the mean temperature of days below 0 ºC (freezing) in the Central Pyrenees. Similar results were observed in other mountain badland areas (Nadal-Romero and Regüés, 2010). Decroix and Olivry (2002), in the badlands of the French Southern Alps, concluded that marls are weathered during freeze-thaw cycles, provided that the water content is high enough during winter, identifying 100 cycles or more during one year. Gallart *et al*. (2002) indicated that in wet areas, in contrast with dry badlands, freezing cycles and geliviation processes are much more important than wetting-drying cycles, as it is shown in Figure 1b. Similar results were obtained by Regüés *et al*. (1995), which concluded that the most important physical weathering agents are freezing and frequent freeze-thaw cycles at high moisture levels (although it is only evident in the first 10 cm), suggesting that desiccation plays only a secondary role in physical weathering.

Rainfall variables control the hydrological and erosion dynamics of wet badlands (Figure 1b), in accordance with the results obtained in dry badlands. Piqué *et al*. (2014) indicated that runoff in the Central Pyrenees is highly dependent on rainfall and antecedent moisture content. Similar results were also reported for other Mediterranean mountain badlands (López-Tarazón *et al*., 2010; Nadal-Romero *et al*., 2018a; Tuset *et al*., 2016). Erosion processes, in general, are a function of rainfall duration, magnitude and intensity (Figure 1b). Descroix and Olivry (2002) indicated that erosion dynamics is mainly controlled by rainfall amount and rainfall intensity and effective rainfall, suggesting that the most erosive events are caused by intense and short rainfalls. Also, Mathys *et al*. (2003) and Bechet *et al*. (2016) indicated that the main climate-driver is rainfall amount (threshold > 9 mm) and rainfall intensity (> 60 mm $h^{-1}$), highlighting the importance of extreme rainfall events. Buendía *et al*. (2016) showed that rainfall intensity together with temperature regime determine erosivity and weathering processes, and thus sediment production. López-Tarazón *et al*. (2009, 2010) concluded that the main drivers are rainfall duration and total rainfall (the longer the duration the higher the sediment yield). In the Western Italian

Alps, Bollati *et al*. (2019) also highlighted the importance of drought periods alternating with wet periods and the occurrence of extreme rainfall events.

All this together provided an overall picture of the main climate-drivers governing badlands hydro-geomorphological response. However, other factors, such as lithology could also influence the hydro-geomorphological response of badland areas. In that sense, it should be highlighted the important role played by lithology in the rate of weathering in badland areas, regardless of precipitation and temperature. A high number of authors consider lithology "as the main factor controlling badland distribution and morphological diversity under the montane Mediterranean conditions" (Moreno-de las Heras and Gallart, 2016, p. 107) (see also Moreno-de las Heras and Gallart, 2018). Thus, swelling lutites tend to increase in volume during short rainy periods causing bedrock weathering due to repeated wetting-drying cycles, particularly in sub-humid and humid areas. The presence of salts in both lutites and marls also contribute to a rapid and deep bedrock weathering, reducing "the chances for seed germination and plant establishment, particularly in drylands" (Moreno-de las Heras and Gallart, 2018, p. 40). Besides, the presence of exchangeable sodium in lutites enhances the probability of occurrence of clay dispersion, leading to subsurface erosion (García-Ruiz, 2011; Faulkner, 2013; Kasanin-Grubin *et al*., 2018). Some authors also attributed to well-sorted fine sediments a high probability of disintegration and piping, and ultimately to badland development (Kasanin-Grubin *et al*., 2018).

Likewise, it should be mentioned that the main processes and the effect of climatic drivers varies at different spatial and temporal scales (Nadal-Romero *et al*., 2011). For example, the influence of drivers affecting weathering processes will be more important for total sediment yield in small catchments than in large areas with numerous sediment sinks. Thus, further research should address the influence of climatic drivers on the operating processes in badlands at different spatial scales (hillslope, micro-catchment, medium and large catchments) and their interconnections over different temporal scales (event, seasonal, intra-annual, inter-annual).

### *3.2. Climate-drivers and hydro-geomorphological dynamics interactions: El Cautivo and Araguás catchments*

The structural equation modelling presented in Figure 2 provides a comprehensive view of the major climate-drivers controlling the hydro-geomorphological response of two representative sites of dry (El Cautivo, Figure 2a, p-value 0.356 and NFI and GFI > 0.9) and wet (Araguás, Figure 2b, p-value 0.335 and NFI and GFI > 0.9) Mediterranean badlands. These SEM models also allow to assess the relative importance of the climate-drivers (R, $I_5$max, $R_{-3day}$, and W-D or Fdc) and their interactions on badland runoff and erosion. Testing the direct and indirect relationships between drivers and response variables (RR, RC, Qmax and SY) also contribute to disentangle the interactions of weathering, runoff and erosion underlying the functioning of both badlands. A good model fit was obtained in both sites (see Table S2 of the Supplementary material).

The SEM explained 57% and 62% of variance in RC and SY, respectively, for El Cautivo site (Figure 2a) and 52% and 59%, respectively, for Araguás site (Figure 2b). In both models, R (with the highest effect, see Table S2 Supplementary Material) and $I_5$max showed a significant direct effect on Qmax, which in turn had an indirect effect on RC through its direct effect on the increase of RR. Previous studies have also shown that rainfall amount and intensity are the main drivers for Qmax in dry (Cantón *et al*., 2001b) and wet Mediterranean badlands catchments (Llena *et al*., 2020; Nadal-Romero *et al*., 2018a). In addition, $R_{-3day}$ exerted a significant direct effect on Qmax at the Araguás catchment (Nadal-Romero *et al*., 2018a). These results agree with previous studies at this site that support that rainfall characteristic and pre-event conditions (catchment moisture) play an important role in determining the magnitude of the hydrological response (Nadal-Romero *et al*., 2018a). At both sites, a direct negative effect of $I_5$max on RR was found, attributed to the fact that most intense rainfalls had a short duration and occurred during periods of low antecedent moisture (summer and the beginning of autumn). This produces lower runoff amount than low-intensity but long-lasting rainfalls that fall mainly during the winter season, when antecedent moisture is high and runoff generates rapidly (Chamizo *et al*., 2012).

Rainfall and runoff influenced SY, but with contrasting effects for the dry and the wet catchments. Qmax was the main driver for SY and showed a significant direct effect on SY at both sites (path coefficients of 0.46 and 0.56 for El Cautivo and Araguás, respectively). However, while $R_{-3day}$ had a significant positive effect on SY at El Cautivo, it showed a negative effect at Araguás. This negative effect is mainly explained by the seasonal dynamics observed in the Araguás catchment: high moisture conditions were observed in spring and winter when low SY values were recorded. Thus, sediment transport during spring and winter depended mainly on Qmax, while in summer and autumn on rainfall intensity and Qmax. In El Cautivo, the occurrence of rainfalls large enough to generate runoff are scarce (according to Cantón *et al*. (2001b), only 16% of rainfall exceeded the threshold for runoff generation), being rainfall amount the most important driver for SY (see Table S2

Supplementary Material), and $I_5max$ was the second one, whose importance was also previously highlighted by Solé-Benet *et al*. (2012) in these badlands. Conversely, for the wet badlands, where R is less constricting, $I_5max$ arises as the main climate-driver for SY (Table S2 Supplementary Material), as has been previously reported by Nadal-Romero *et al*. (2018a). Rainfall intensity ($I_5max$) also indirectly influenced SY at both sites through their significant direct effect on Qmax.

Contrary to expectations, wetting-drying cycles did not exert a significant effect neither on runoff amount nor SY at El Cautivo catchment. At this site, the majority of rainfalls (more than 84%) do not generate runoff but promote sequential wetting-drying cycles able to induce weathering rates of up to 201.47 t $ha^{-}1$ $y^{-1}$. These rates are much higher than the SY rates of 5.3 t $ha^{-1}$ $y^{-1}$ recorded at plot scale on bare marl during the same period (Cantón *et al*., 2001a, 2001b). Thus, SY in this dry badland system is not limited by weathering but by the occurrence of low-recurrence rainfalls able to generate extreme runoff events and to transport the available sediment (Cantón *et al*., 2001b). In contrast, at Araguás, Fdc did show a significant direct effect on SY. Detailed studies in the Araguás catchment showed that SY depends on the availability of sediment susceptible to be transported, highlighting the temporal delay between the weathering and erosion processes and sediment transport (Nadal-Romero and Regüés, 2010).

### *3.3. Projected climate changes and its impacts in Mediterranean badland dynamics*

Climate changes related to hydro-geomorphological processes in the Mediterranean region mainly include changes in temperature and precipitation, the latter being the most direct influencing factor for soil erosion at the global scale (Li and Fang, 2016). Since badlands are very active from a geomorphological point of view, such changes are expected to be highly prominent. The magnitude and direction of changes will depend on the interaction of climate change with soil properties, vegetation cover or land management. Thus, regional differences in this response are expected, and special attention should be paid on how climate-drivers governing the hydro-geomorphological response will be modified in the future. Figures 3, 4 and 5 summarize the variations of the most important climate-drivers previously identified (section 3.1) by 2050, according to climate forecast obtained by the CMIP5: (i) mean annual rainfall; (ii) SDII; (iii) days with rainfall > 1 mm (as a proxy of the number of precipitation events); (iv) number of frost days; and (v) water content of the soil layer.

An overall decrease in annual rainfall is expected (Figure 3a), affecting almost the entire Mediterranean basin (with some exception in the Alps, where most wet badlands are located). Changes are especially relevant in dry badlands, where a decrease of total rainfall between 3% and 10% of the current value is expected, depending on emissions scenario (Figure 3a; Supplementary Figure 3). Rainfall intensity showed the opposite pattern with an overall increase between 2 and 5% (Figure 3b). This variation could be underestimated if we compared our results with these obtained by regional circulation models which better capture the influence of orography in rainfall, but a similar pattern is expected (Conte et al., 2020). In all scenarios, higher changes are expected in central, northern and southern-Italy, and lower changes are expected in southeastern Spain (Figure 3b; Supplementary Figure 4). Climate-drivers modulating weathering processes will be also affected. For example, as observed in Figure 4, a marked decrease in the number of rainfall (Figure 4a; Supplementary Figure 5) and frost days (Figure 4b; Supplementary

Figure 6) is expected by 2050, which may severely affect wetting-drying and freeze-thaw cycles. A substantial decrease in soil moisture, ranging from -2 to -10%, is also projected as a result of the increased temperature and decreased precipitation (Figure 5; Supplementary Figure 7). This decrease, especially relevant in wet badlands, will have direct hydro-geomorphological implications and also some indirect effects.

Given the direct relationship between rainfall characteristics and the hydro-geomorphological response (Figures 1 and 2), the slightly decrease in rainfall amount (Figure 3a), and the marked increase in rainfall intensity (Figure 3b) and in the occurrence of more frequent extreme events (Supplementary Figure 8) suggest that badlands will produce lower runoff volumes but greater erosion rates in the near future. However, a general decrease in the number of frost days, number of rainfall events and soil moisture content is expected (Figures 4 and 5). This, together with an increase in temperature and a decrease in the ratio of snow to rain (Navarro-Serrano and López-Moreno, 2017), would reduce weathering processes, sediment availability and subsequent erosion rates, as it is observed and modeled by Clarke and Rendell (2010). Therefore, a future increase of erosion in Mediterranean badlands could be only expected in areas where sediment availability is not limited by weathering dynamics.

The reduction in total rainfall and wetting-drying cycles in dry badlands (Figures 3 and 4) would lead to a decrease in annual runoff and erosion rates. These predictions fit well with preliminary studies that described a decrease in annual interrill erosion rates in Mediterranean badlands over the last decades (Clarke and Rendell, 2010). However, as observed in Figure 1 and later corroborated by SEM analysis (Figure 2), sediment availability and weathering seem to play only a minor role in dry badlands at the catchment scale. Here, the occurrence of intense rainfalls of magnitude sufficient to connect hillslope runoff to the main channel network seems to be the main driver (Khun *et al*., 2004; Faulkner, 2008; Godfrey *et al*., 2008; Rodríguez-Caballero *et al*., 2014).

As both rainfall intensity (Figure 3a) and the occurrence of extreme rainfalls (Supplementary Figure 8) will increase in most dry Mediterranean badlands, higher soil erosion would occur. This will be also enhanced by the expected negative effects that increased aridity, and more prolonged drought periods (Lehner *et al*., 2006) will play on the scarce plant cover. This will enlarge the size and extent of open areas where runoff is generated. Biological soil crusts, which often cover these open areas will be also negatively affected, conditioning runoff generation, flow connectivity and water erosion in dry badlands (Rodríguez-Caballero *et al*., 2014, 2018b; Yair *et al*., 2011). Vegetation loss, decrease in biocrust coverage and a replacement of well-developed biocrust communities by early incipient ones will exacerbate interrill erosion and could lead to the formation of rills, increasing flow connectivity (Rodríguez-Caballero *et al*., 2015) with the consequent increase in SY.

Similarly, as observed in dry badlands, most of the forecasted climate-driver changes would reduce weathering processes in wet badlands, due to a decrease in the number of frost days and soil moisture content (Figures 4 and 5). These changes will therefore result in a decrease in sediment supply, and a consequent increase in fluvial erosion because streams tend to scour their channels to compensate the declining sediment arriving from the slopes (e.g. Liébault *et al*., 2005; Beguería *et al*., 2006; Keesstra, 2007; Sanjuán *et al*., 2016). Thus, the hydrological responses would be characterized by rapid and intense runoff, but sediment dynamics may be less marked. This fact would enhance a natural revegetation of the slopes and its stabilization. But, what is expected to happen with vegetation dynamics in wet Mediterranean badlands? Current vegetation growth in wet badlands is limited no longer by water availability, as occurs in dry areas (Maestre *et al*., 2016), but by weathering processes associated to freeze-thaw cycles, particularly on north-facing slopes, and by high erosion rates, preventing the natural regeneration of vegetation (Gallart *et al*., 2013b; Moreno-de las Heras and Gallart, 2016; Betron *et al*., 2016; Francke *et al*., 2018). Climate scenarios and expected hydro-geomorphological dynamics suggest a change in regolith dynamics, allowing the colonization and persistence of well-developed biocrust communities that would contribute to reduce water erosion. A slightly decline in weathering and erosion processes will have an impact on vegetation cover, suggesting that vegetation growing would be enhanced in wet badlands.

### 3.4. Off-site effects of Mediterranean badland areas under a context of Global Change

Badlands are major contributors of sediment to the fluvial network (García-Ruiz *et al*., 2013, 2017). Despite of their small size with regards the total area of river basins (badlands proportion in the catchments with an area >$10^6$ ha is rarely more than 5%, Copard *et al*., 2018) they provide a significant sediment supply to river networks (14% of the total sediment fluxes in the Rhône River, Copard *et al*., 2018). Badland contribution to sediment load in Mediterranean areas is even higher, increasing by a factor of 7 to 8 the sediment deliveries (Nadal-Romero *et al*., 2011). Uber *et al*. (2019) concluded that marly badlands are the main source of suspended sediment for the Caludègne catchment, and Palazón *et al*. (2016) stated that although badlands occupy only 1% of the Barasona reservoir catchment in the Ésera River basin, Spanish Pyrenees, they are the main suspended sediment source for reservoir siltation, reducing rapidly its storage capacity. Thus, any alteration in the badlands hydro-geomorphological functioning, as these expected by Global Change, may have direct impacts on sediment transfer, including channel clogging, alluvial plain dynamics alteration, water quality or reservoir siltation. Moreover, varying sediment supplies/deliveries to the river cause the channel banks to alternate over time between supply-limited and transport-limited situations, leading to an impact on geomorphological evolution of the river channel (Juez *et al*. 2018a).

Changes related with badlands sediment supplies have implications in the carbon cycle since sediment traps organic carbon (Battin *et al*., 2009). Thereby, sediment yield through weathering and erosion processes can be seen as a major contributor to the organic carbon cycle at continental scale (Copard *et al*., 2007). Recent studies show that the role of badlands in the carbon cycle, as major sediment sources, may depend on the physical and chemical properties of the parent material and on the aggressiveness and duration of the weathering processes (Graz *et al*., 2012; Copard *et al*., 2018). Carbon attached to the sediment may ultimately be stored in reservoirs (Schleiss *et al*., 2016) or can be exported to the oceans (Copard *et al*., 2018). Unfortunately, the knowledge on the significance of badlands in the carbon cycle at a regional or global scale is still limited (Galy *et al*., 2015; Copard *et al*., 2018), and could be modified due to new scenarios proposed by Global Change.

Our analysis of the main climate-drivers controlling the response of Mediterranean badlands to Global Change reveals that the hydro-geomorphological off-site effects could be enlarged, with more frequent and intense floods, increased river and reservoir sediment yield, as well as the worsening in the quality of water bodies. Thereby, understanding the current and future sediment supplies from badlands and their role in the carbon cycle is crucial to plan proper adaptation strategies to face the impacts of Global Change. Additionally, this is extremely important in water bodies affected by disturbances in their sediment continuum cycle due to the presence of reservoirs (Schleiss *et al*., 2016; Juez *et al*., 2018b, 2018c).

We are conscious of the difficulties to project changes for the coming decades in badland areas because of the strong interactions between land use changes and erosion. In general, human activities can induce drastic alterations in rainfall partitioning, soil and plant characteristics, and overland flow. Some badland areas can be subjected to increased human pressure, especially in semiarid regions affected by population growth and grazing in marginal territories. In such cases, pressure over badland regions can increase the already high erosion rates that characterized these systems (e.g. Nadal-Romero *et al*., 2011) and consequently many efforts should be made to reduce the high rates of sediment yield, although such practices are rarely successful (Nadal-Romero and García-Ruiz, 2018; Rey *et al*., 2003). However, most badlands are affected by an abandonment of grazing, including the surrounding areas, and this should enhance plant recovery in the margins of badlands with the consequent reduction in the access of overland flow into the gullies of the badlands. In any case, this is an extremely complex topic that merits a special scientific focus in the next few years.

## 4. Conclusions

The hydro-geomorphological response of Mediterranean badlands is strongly affected by climate variables, with different interrelated drivers operating at different temporal and spatial scales in dry and wet regions.

Future scenarios for climate-drivers in the Mediterranean region include declining rainfall volumes, and a decrease in the number of frost days and rainfall events, and in soil moisture content, as well as an increase in rainfall intensity. These changes, together with the foreseeable human impact and land cover changes are likely to amplify and modify Mediterranean badland dynamics. The direct and indirect effects of all these drivers interact in a Global Change context to configure an uncertain and complex response of badland systems. Thus, the analysis of the hydro-geomorphological response of badlands to climate change should be done in an overall context that includes, not only the direct effects of climatic drivers on the hydro-geomorphological response, but also all potential indirect interactions between different drivers and processes. Moreover, as the main processes governing hydro-geomorphological response and the influence of climatic drivers on them varies between dry and wet badlands, this should be studied separately. Based on our analysis and interpretations we conclude that:

(i) Wetting-drying cycles are the main drivers for weathering in dry badlands, while rainfall amount and rainfall intensity were identified as the main drivers for runoff and erosion, respectively. In dry badlands, the predicted increase in rainfall intensity and frequency of extreme events will lead to an increase in erosion. The expected increase in aridity will have a negative impact on vegetation and biocrust cover, enhancing interrill erosion and overland flow connectivity in the bare areas, eventually emphasizing their off-site effects.

(ii) In wet badlands, weathering is controlled by freeze-thaw cycles. Rainfall amount was identified as the main driver for runoff generation, and this together with rainfall intensity were major controlling factors on erosion. Expected climate changes in these badlands suggest that, although the increase in rainfall intensity could increase erosion rates, weathering processes will decline (due to the decrease in the number of frost days and soil moisture contents), as well as runoff volumes, likely having an effect on erosion reduction in the slopes and favoring the stabilization and revegetation of these slopes due to the improvement of the conditions for vegetation growing.

Continue monitoring of Mediterranean badland dynamics will be necessary to detect and understand future changes, as well as interdisciplinary teams to work on these complex environments. Control and restoration techniques should be considered as adaptation strategies when important erosion rates occur, taking into account local conditions and future global changes. In badland areas where changes are not expected to be dramatic and with reduced off-site impacts, we propose to protect them as educational hotspots and research laboratories.

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## Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Conflict of interest

The authors declare that they have no conflicts of interest.

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**Figure 1.** (a) Non-metric MultiDimensional Scaling (NMDS) ordination of the main hydro-geomorphological drivers from the different Mediterranean badlands. (b) Weight Relative importance of different identified climate-drivers (Rainfall amount, Rainfall intensity, Timing/Seasonality, Wetting-drying cycles, Freeze-thawing cycles, Antecedent soil moisture and Snow) for the main operating processes in badlands (weathering, hydrology, and erosion) in dry (arid, semiarid and dry subhumid) and wet (subhumid and humid) badlands. (data presented in supplementary Table S1).

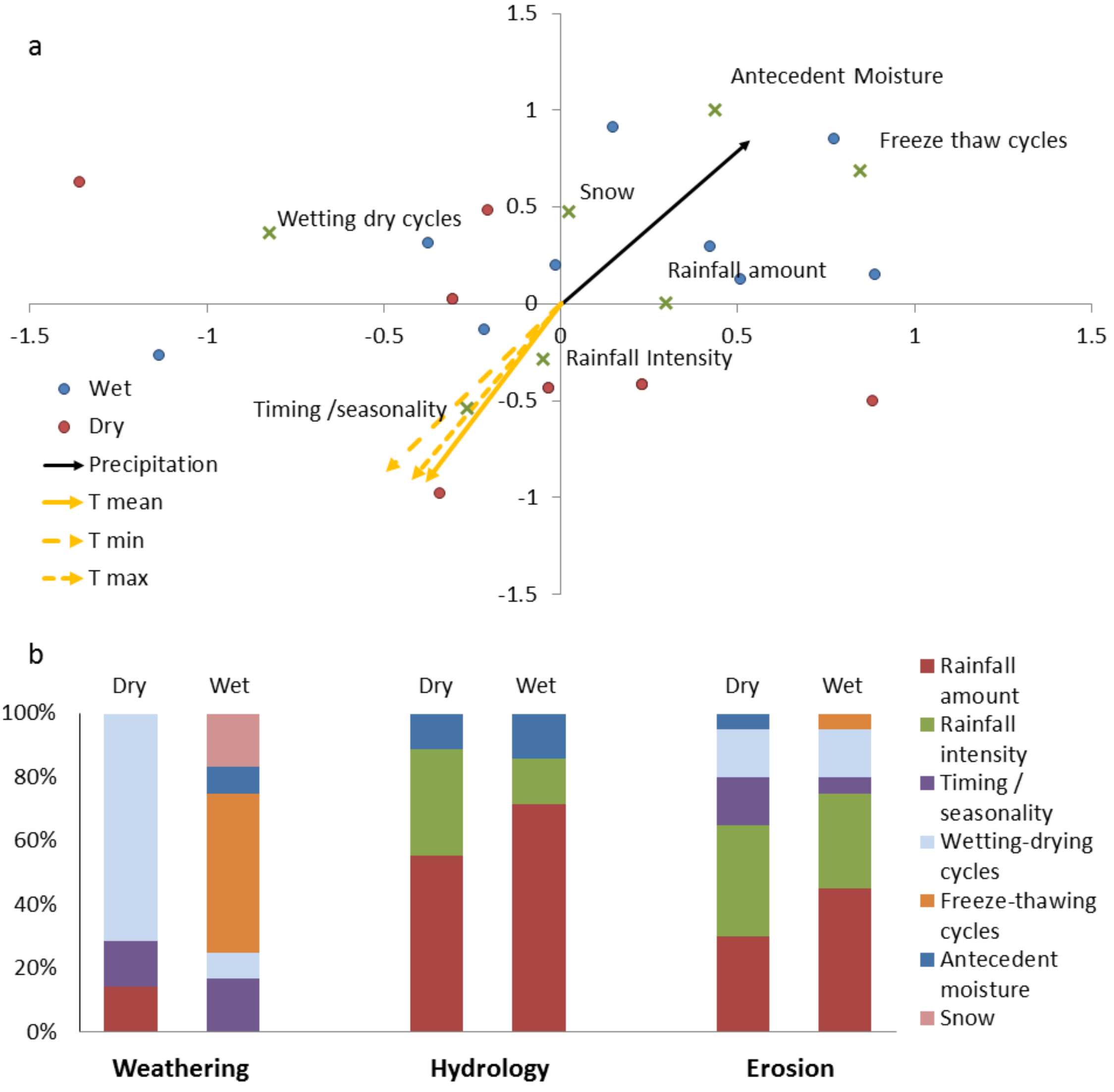
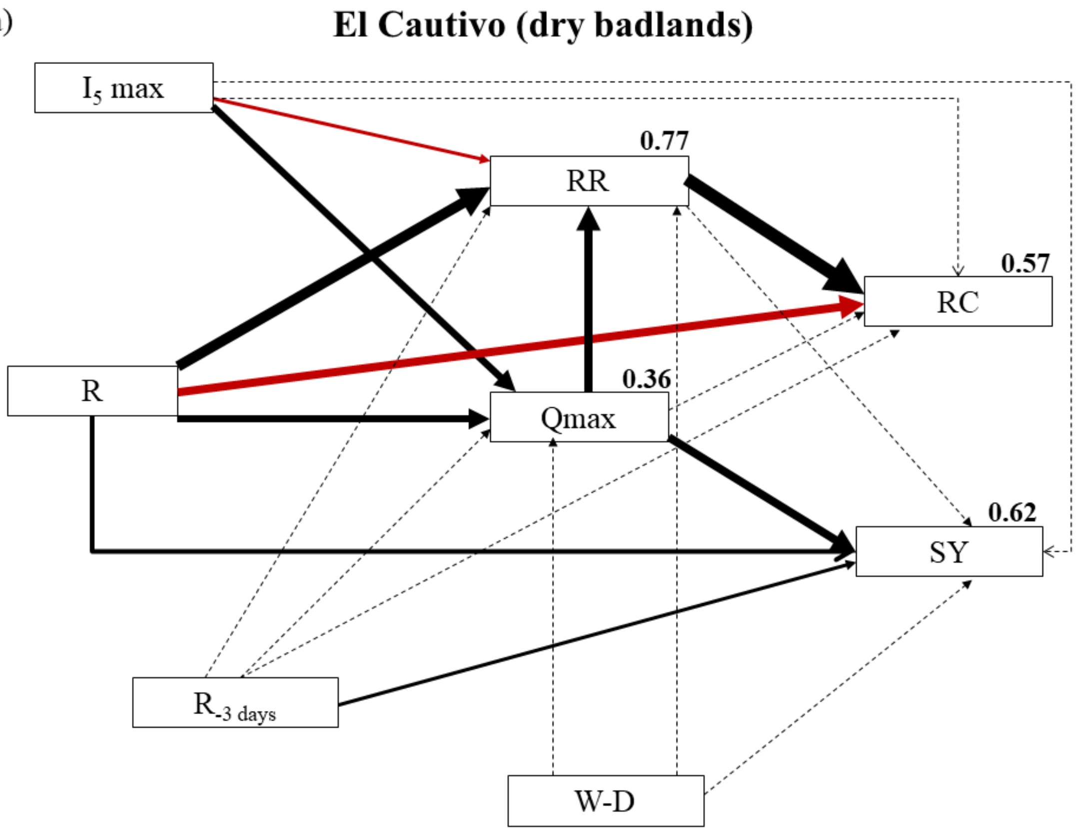
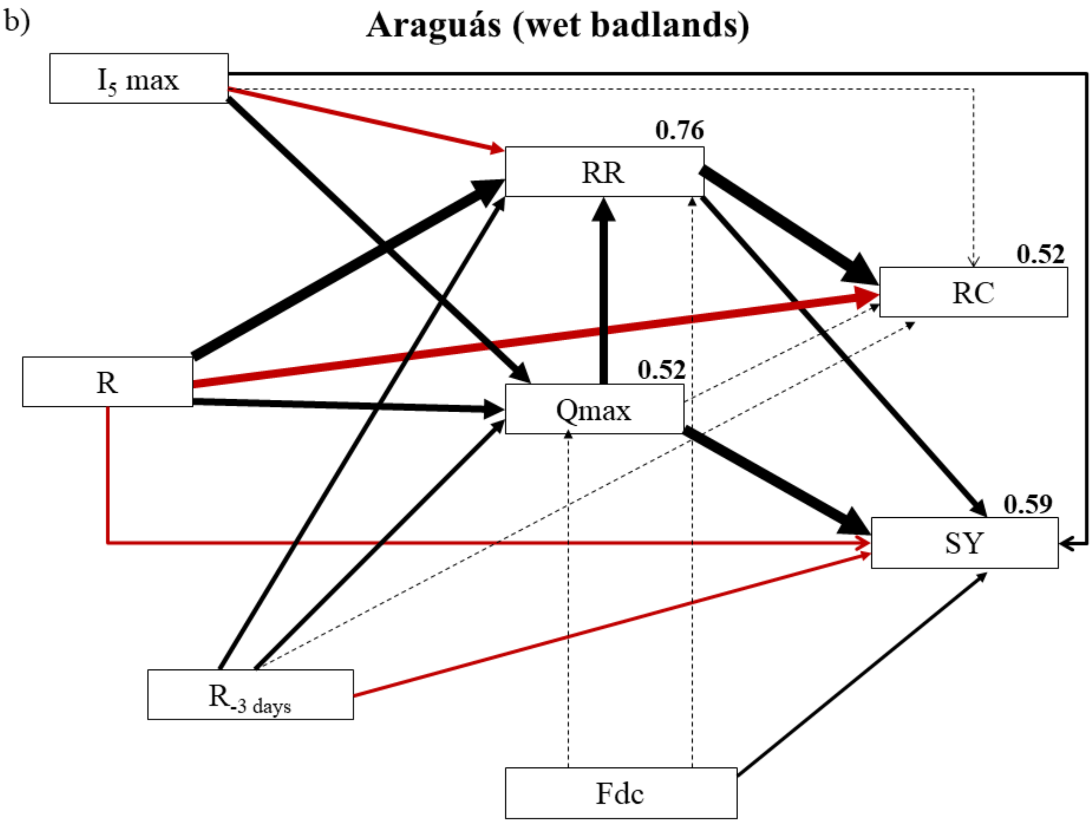


**Figure 2**. Figure 2. Structural equation models (SEM models) showing the relationships between the significant climate-drivers (Rainfall amount [R], maximum rainfall intensity in 5 min [I5max], 3-days antecedent rainfall [R-3 days], and the number of wetting-drying [W-D] and freezing cycles 10 days previous to the event [Fdc]) and the runoff (runoff rate [RR], runoff coefficient [RC] and maximum peak flows [Qmax]) and erosion response (sediment yield , [SY]) in the two study cases: (a) El Cautivo (dry badlands) and (b) Araguás (wet badlands). Both models showed a good fit with p values of 0.357 and 0.335, respectively, and NFI and GFI over 0.9. The number in bold represents the explained variance of dependent variables. Arrow widths are proportional to the magnitude of standardized path coefficients. Black and red arrows indicate positive and negative effects, respectively. Dash lines indicate non-significant paths (p > 0.05). (Rainfall amount [R], maximum rainfall intensity in 5 min [I5max], 3-days antecedent rainfall [R-3 days], and the number of wetting-drying [W-D] and freezing cycles 10 days previous to the event [Fdc]).

a)



b)



Araguás (wet badlands)
I5 max
0.76
RR
0.52
RC
R
0.52
Qmax
0.59
SY
R-3 days
Fdc

**Figure 3.** (a) Expected change in mean annual rainfall (mm d$^{-1}$ /year) and (b) simple daily intensity index (SDII; mm/day) in the Mediterranean basin according to the RCP4.5 of the fifth phase Climate Model Inter-Comparison P. Right plot shows the mean changes (%) based on present values for dry (red) and wet (blue) badlands, including four RCPs. Red circles: dry badlands; blue circles: wet badlands. Maps showing expected changes in mean annual rainfall and SDII for RCP2.6, RCP6.0 and RCP8.5 are shown in Supplementary Figures 3 and 4, respectively.

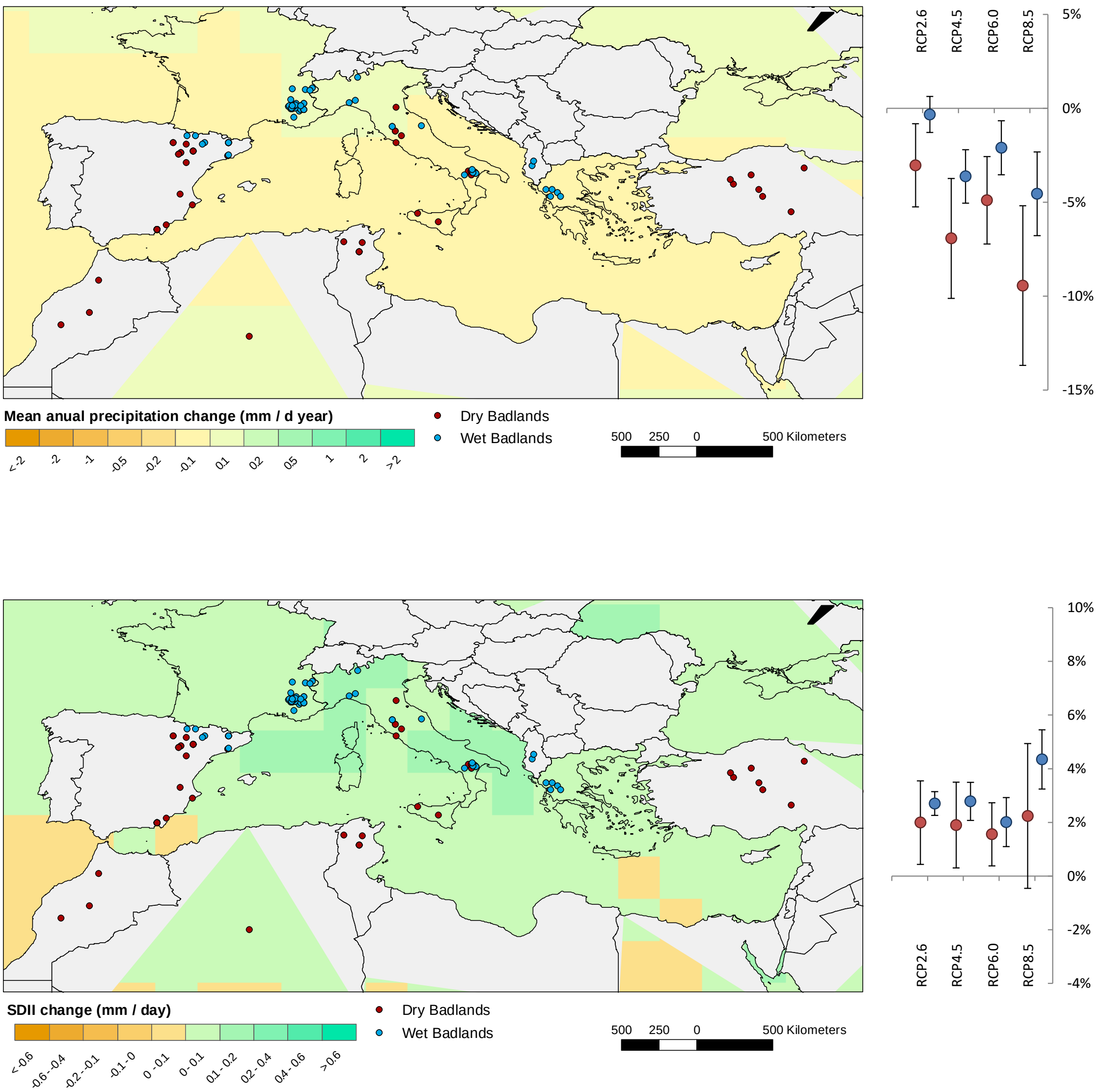


**Figure 4**. (a) Expected change in the number of precipitation events (number of days with total rainfall > 1mm) and (b) number of frost days (number of days with mean temperature < 0º) in the Mediterranean basin according to the RCP4.5 of the fifth phase Climate Model Inter-Comparison Project (change in 2050 compared to 2005). Right plot shows the mean changes (%) based on present values for dry (red) and wet (blue) badlands, including four RCPs scenarios. Maps showing expected changes in the number of precipitation events and frost days for RCP2.6, RCP6.0 and RCP8.5 are shown in Supplementary Figures 5 and 6, respectively.

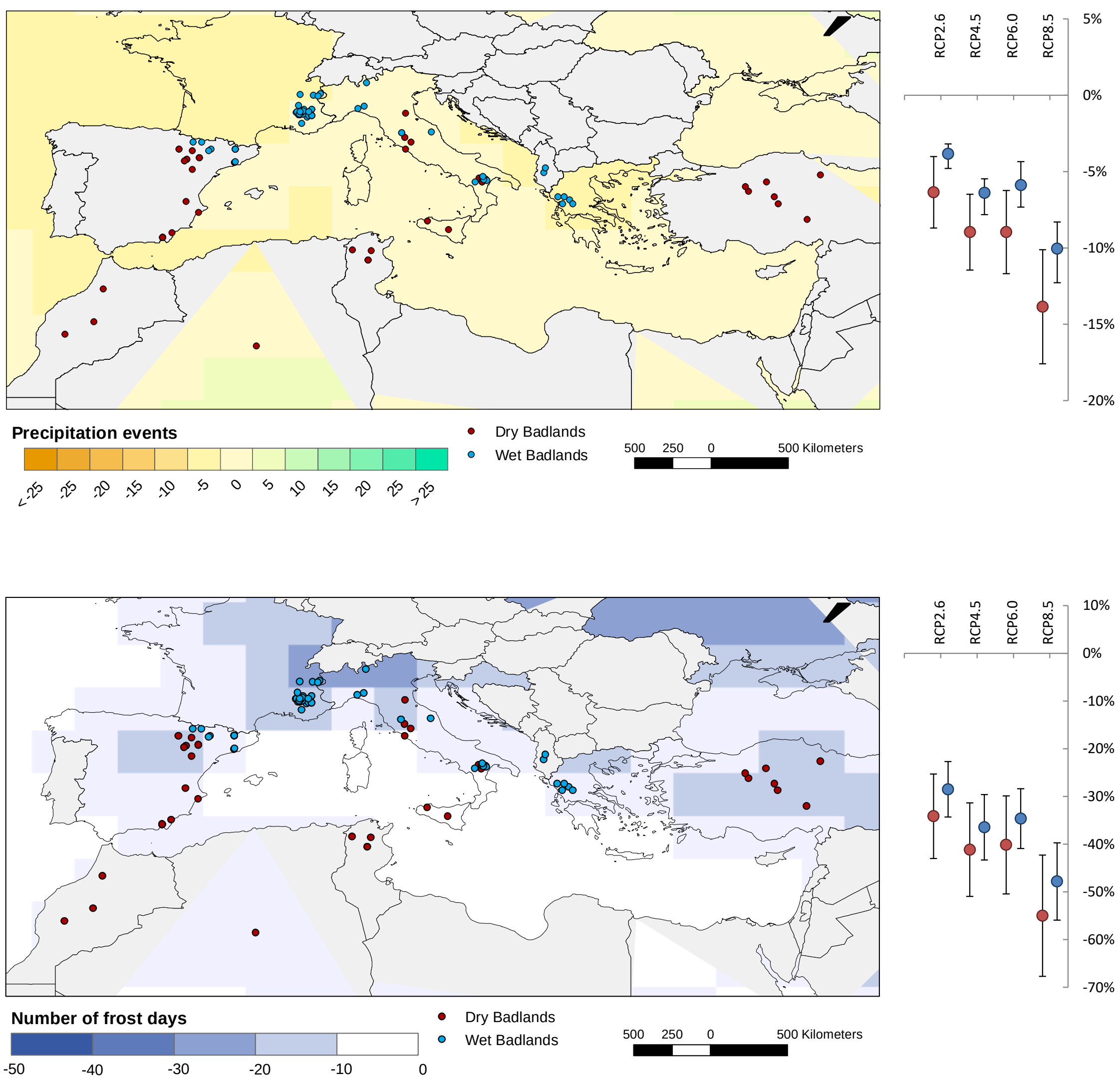


**Figure 5**. Expected change moisture content of the soil layer (kg m$^{-2}$) in the Mediterranean basin according to the RCP4.5 of the fifth phase Climate Model Inter-Comparison Project (change in 2050 compared to 2005). Right plot shows the mean changes (%) based on present values for dry (red) and wet (blue) badlands, including four RCPs scenarios. Maps showing expected changes in moisture content of the soil layer for RCP2.6, RCP6.0 and RCP8.5 are shown in Supplementary Figure 7.

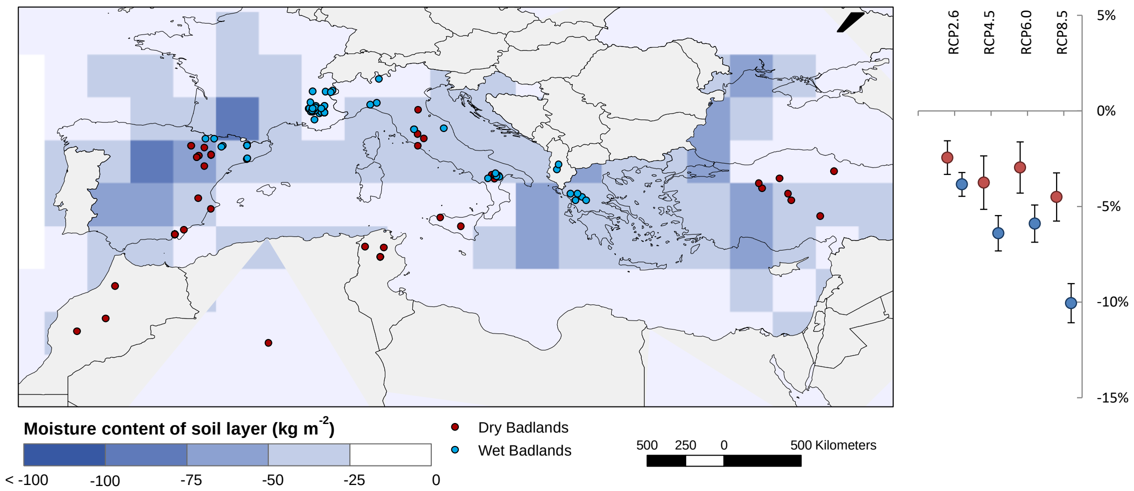


**Table 1.** Defining variables in badland areas in each operating process (weathering, hydrology and erosion) and climatic drivers considering in the analysis.

| Defining variables | | | |
|---|---|---|---|
| **Weathering** | **Hydrology** | **Erosion** | **Climatic drivers** |
| Number of wetting-drying cycles<br>Number of freezing cycles | Runoff coefficient<br>Runoff rate<br>Maximum peak flows | Sediment yield | Rainfall amount<br>Rainfall intensity<br>Timing/seasonality<br>Wetting-drying cycles<br>Freeze-thawing cycles<br>Antecedent moisture |

Supplementary Materials for

## Mediterranean Badlands: their driving processes and climate change futures

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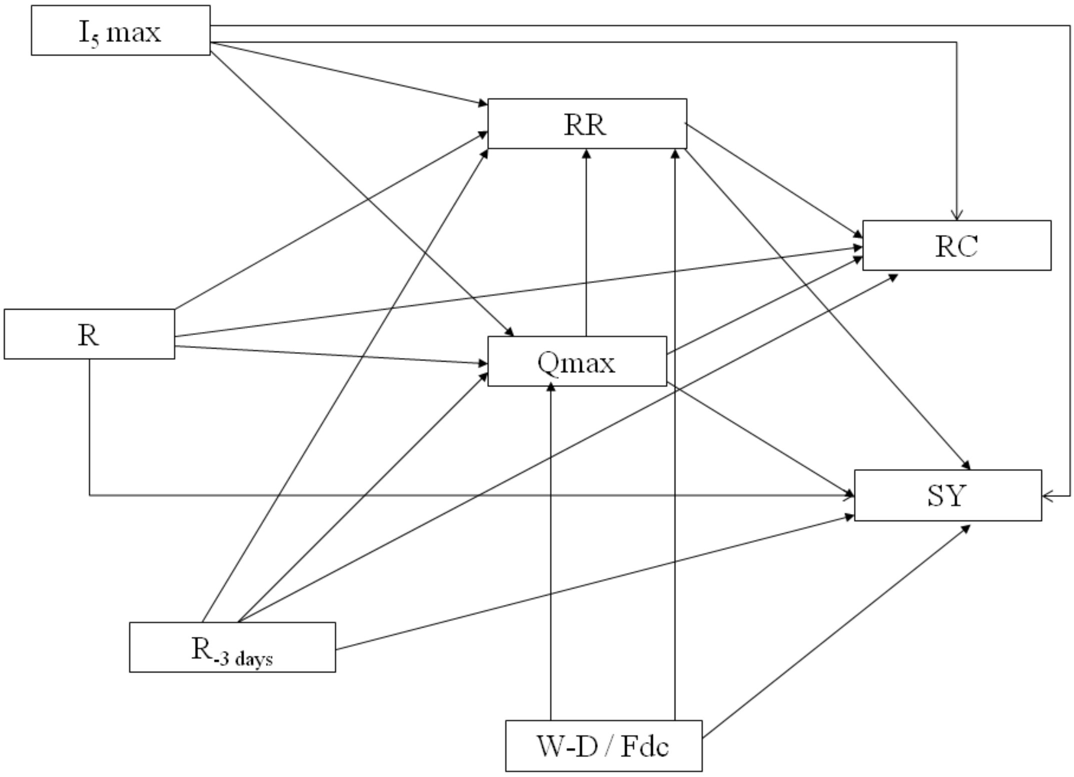
**This PDF file includes:**

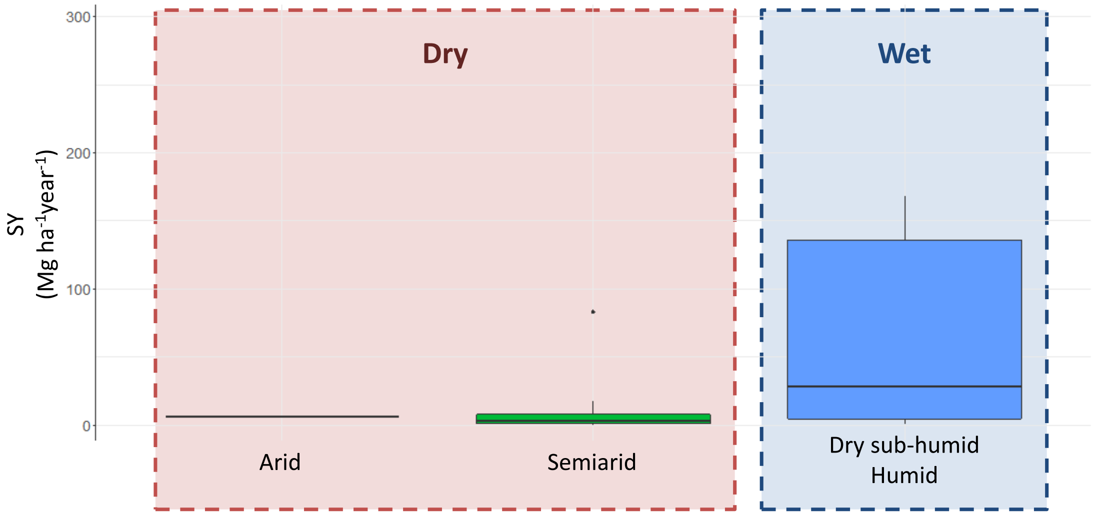
**Supplementary figures:**



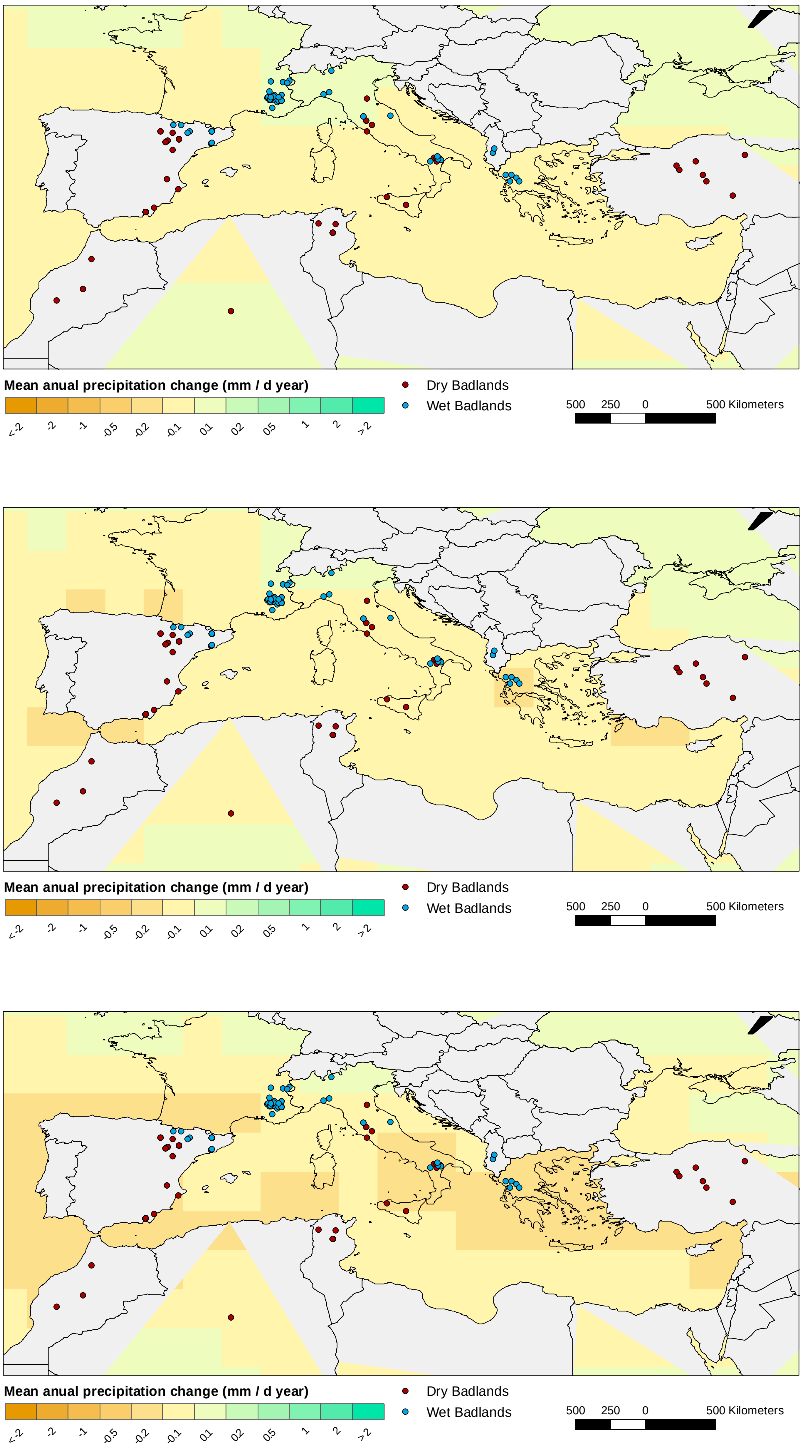
**Supplementary tables:**



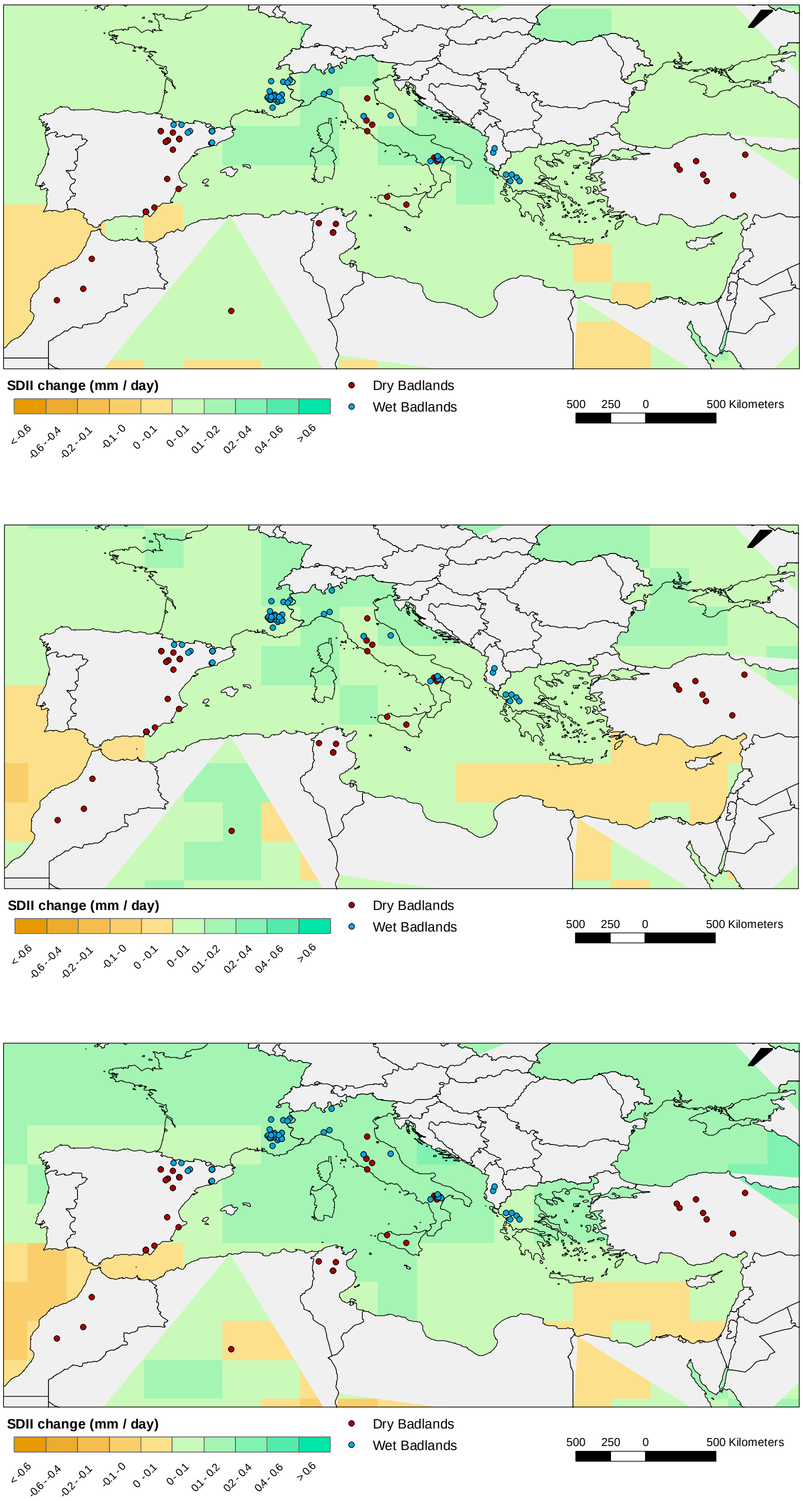

**Supplementary Figure S1**. *A priori model showing the hypothesized causal relationships between the significant climate-drivers (Rainfall amount [R], maximum rainfall intensity in 5 min [I5max], 3-days antecedent rainfall [$R_{-3\ days}$], and the weathering agent (number of wetting-drying [W-D] and freezing cycles 10 days previous to the event [Fdc for dry and wet badlands, respectively]) and the runoff (runoff rate [RR], runoff coefficient [RC] and Qmax) and erosion response (sediment yield, SY).*



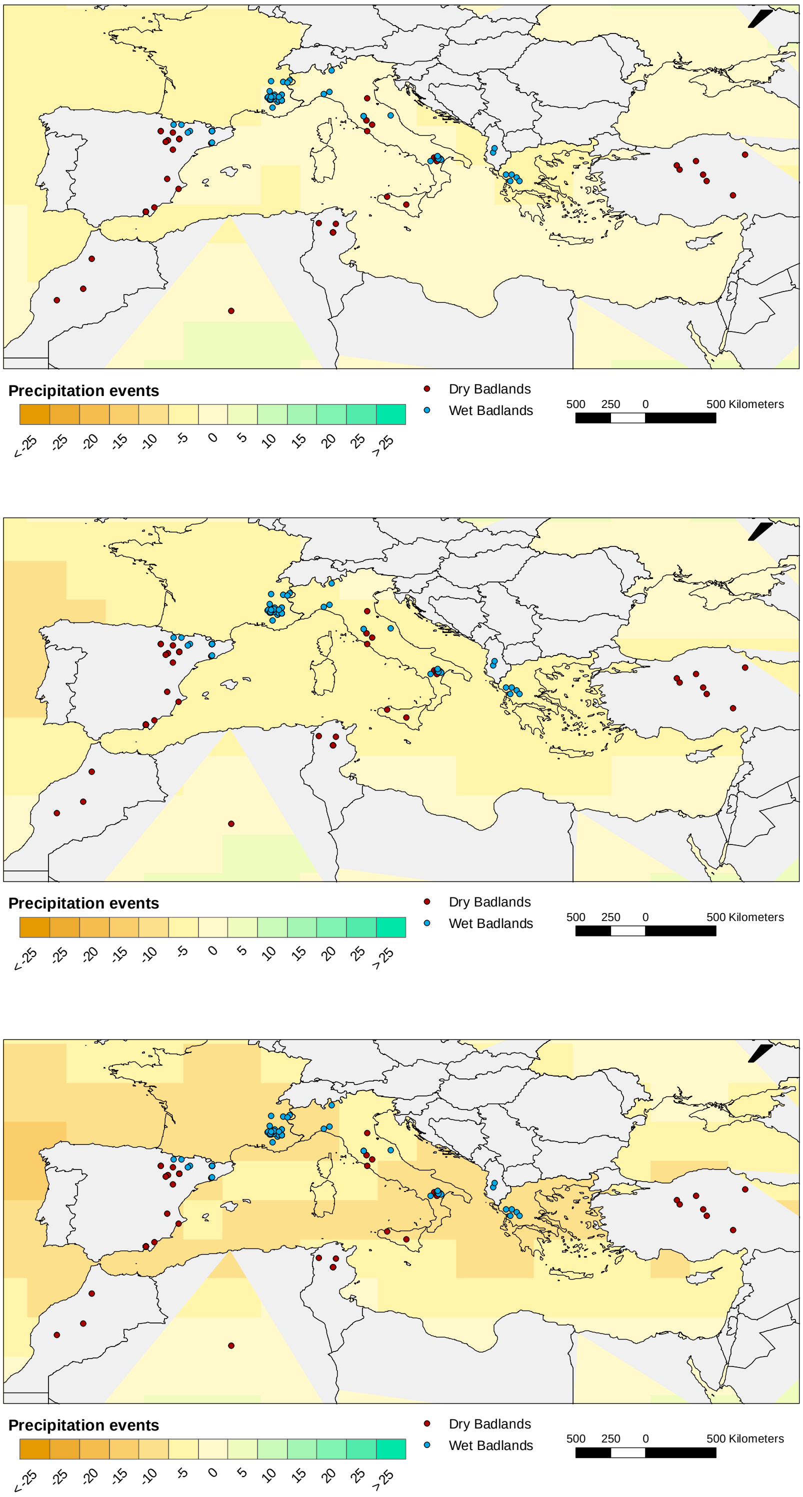

**Supplementary Figure S2.** *Sediment yield (SY, Mg ha$^{-1}$ year$^{-1}$) in dry (arid and semiarid) and wet (subhumid and humid) Mediterranean badlands. Data from Nadal-Romero et al. (2011).*



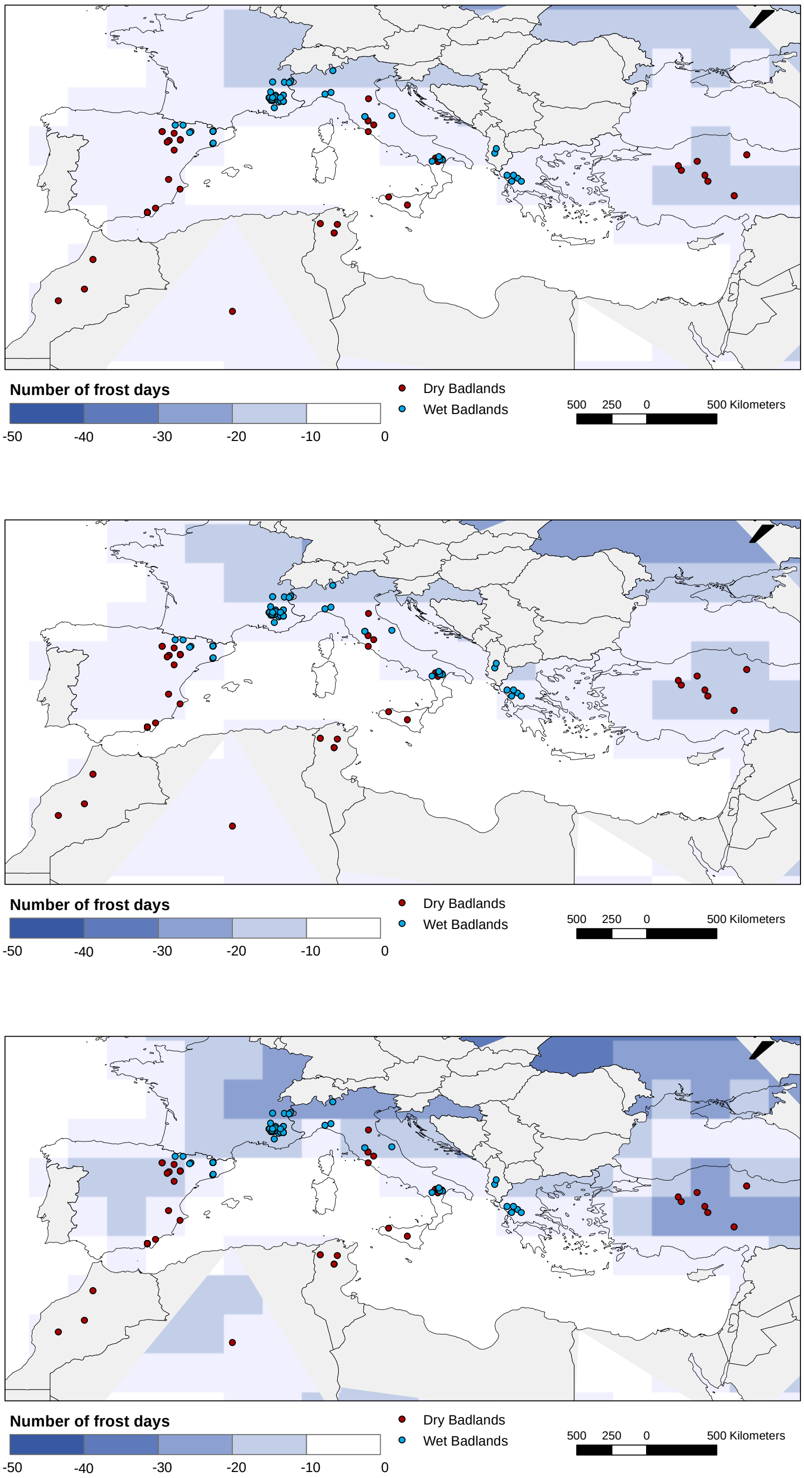

**Supplementary Figure S3.** *Expected change in mean annual rainfall (mm $d^{-1}$ /year) by the year 2050 compared to current conditions in the Mediterranean basin according to the a) RCP2.6 b) RCP6.0, and c) RCP8.5 of the fifth phase Climate Model Inter-Comparison P.*



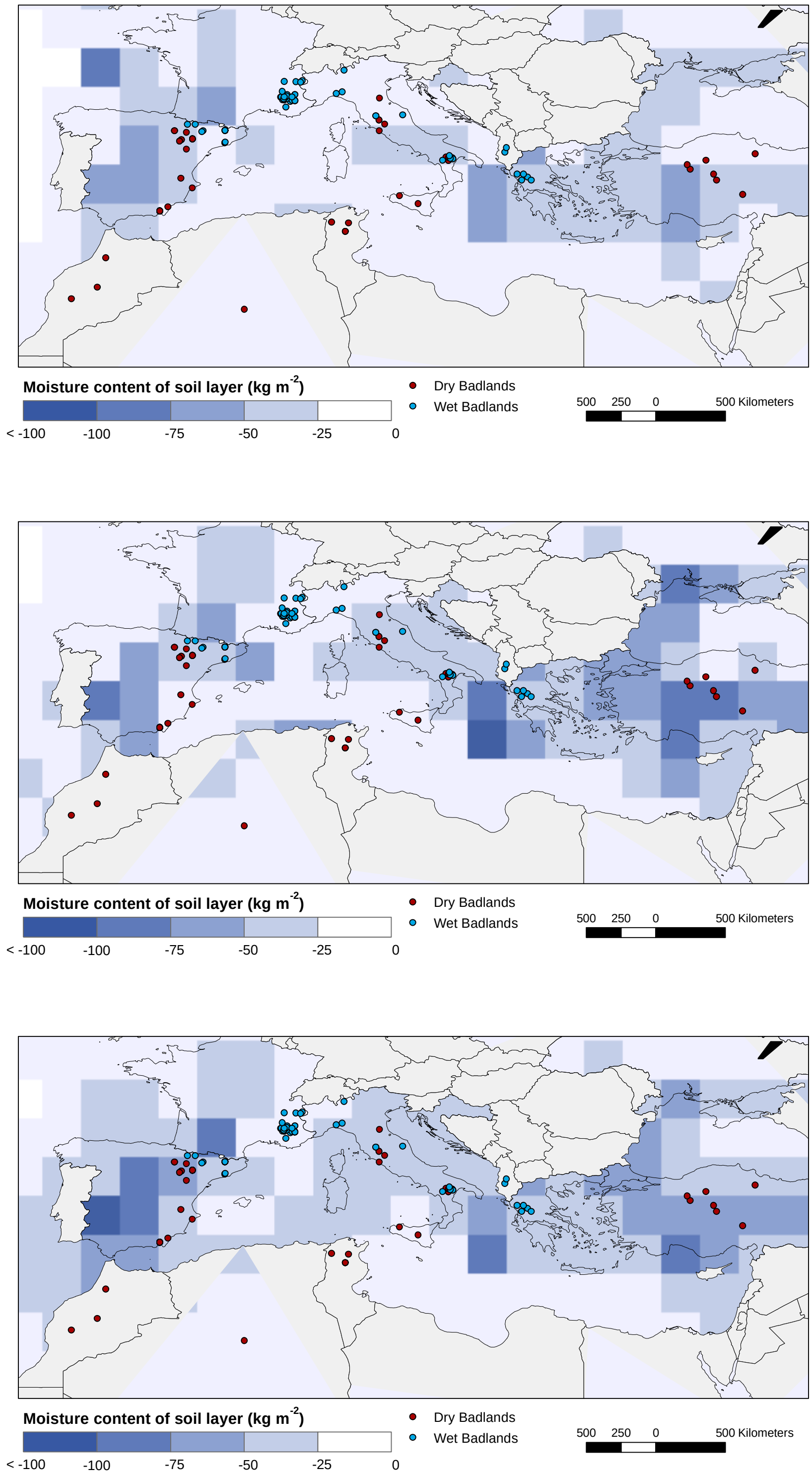

**Supplementary Figure S4.** *Expected change in mean* simple daily intensity index (SDII; Precipitation intensity index (*mm/day) by the year 2050 compared to current conditions in the Mediterranean basin according to the a) RCP2.6 b) RCP6.0, and c) RCP8.5 of the fifth phase Climate Model Inter-Comparison Project.*



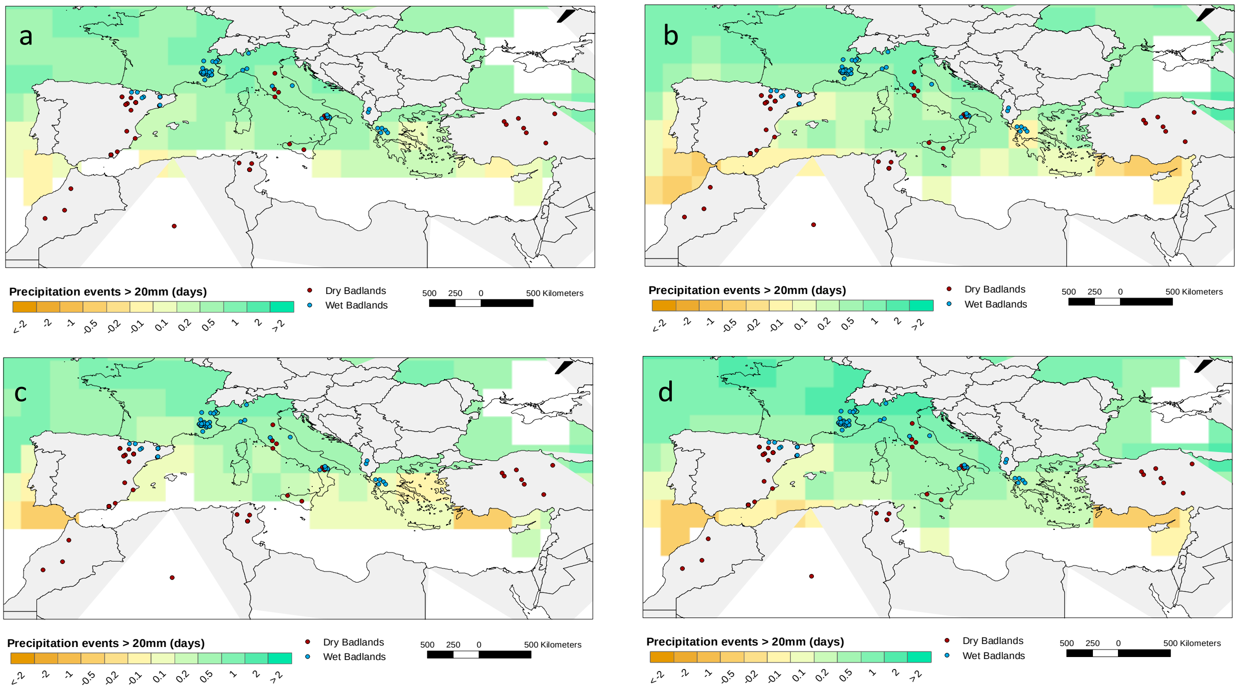

**Supplementary Figure S5.** *Expected change in the number of precipitation events (number of days with total rainfall > 1mm) by the year 2050 compared to current conditions in the Mediterranean basin according to the a) RCP2.6 b) RCP6.0, and c) RCP8.5 of the fifth phase Climate Model Inter-Comparison Project.*




**Supplementary Figure S6.** *Expected change in the number of frost days (number of days with mean temperature < 0º) by the year 2050 compared to current conditions in the Mediterranean basin according to the a) RCP2.6 b) RCP6.0, and c) RCP8.5 of the fifth phase Climate Model Inter-Comparison Project.*




**Supplementary Figure S7.** *Expected change in moisture content of the soil layer (kg $m^{-2}$) by the year 2050 compared to current conditions in the Mediterranean basin according to the a) RCP2.6 b) RCP6.0, and c) RCP8.5 of the fifth phase Climate Model Inter-Comparison Project.*




**Supplementary Figure S8.** *Expected change in extreme rainfall events (number of days with total rainfall > 20mm) by the year 2050 compared to current conditions in the Mediterranean basin according to the a) RCP2.6, b) RCP4.5, c) RCP6.0, and d) RCP8.5 of the fifth phase Climate Model Inter-Comparison Project.*

**Supplementary Table S1.** Main climate-drivers identified in the different study sites for weathering, hydrology and erosion processes.

| Country, study site | MAP (mm) | MAT (ºC) | Weathering drivers | | | | | | Hydrology drivers | | | | | | Erosion and Sediment yield drivers | | | | | | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | R | W-D | F-T | Sn | T/S | Ant moist | R | I | W-D | F-T | T/S | Ant. moist | R | I | W-D | F-T | T/S | Ant. moist | |
| France, Pre Alps | 900 | 10.9 | | ● | ● | | ● | | ● | ● | | | | | ● | ● | | | | | 2, 3, 14, 16, 28, 37 |
| Israel, Zin Valley | 91 | 17 | | | | | | | ● | ● | | | | | ● | | | | ● | | 21, 22, 44 |
| Israel, West Bank | 156-532 | - | | | | | | | ● | ● | | | | | | | | | | | 38 |
| Italy, Basilicata | 738 | 17 | | | | | | | | | | | | | ● | ● | ● | | ● | | 6, 10, 12, 13, 32, 33 |
| Italy, Gran Gorgia | 848 | 16 | | | | ● | | | | | | | | | ● | ● | ● | | | | 4 |
| Italy, Northern Apennines | 723 | 12.9 | | | | | | | | | | | | | ● | ● | | | | | 5 |
| Italy, Upper Orcia | 700 | 14 | | | | | | | | | | | | | ● | ● | | | ● | | 1, 6, 15, |
| Italy, Sicily | 620 | - | | | | | | | | | | | | | | ● | | | ● | | 6 |
| Italy, Calabria | 700 | 19.7 | ● | ● | | | ● | | | | | | | | | | | | | | 34 |
| Morocco, Eastern Rift | 150-350 | - | | | | | | | | | | | | | | | | | | | 42 |
| Spain, Tabernas | 235 | 17.8 | | ● | | | | | ● | ● | | | | | ● | ● | | | | | 8, 9, 39, 40, 41 |
| Spain, Pyrenees | 890 | - | | | | | | | | | | | | | | | | | | | 11 |
| Spain, Bardenas | 350 | 13 | | ● | | | | | ● | | | | | | ● | ● | | | | | 17, 18 |
| Spain, Eastern Pyrenees | 862 | 9.1 | | | ● | ● | | | | | | | | | ● | ● | | | | | 19, 20, 29, |
| Spain, Isabena river | 767 | 10 | | | ● | | | | ● | | | | | ● | ● | | | | | | 24, 25 |
| Spain, Soto basin | 755 | 13 | | | ● | | | | ● | | | | | | ● | | | | | | 23 |
| Spain, Penedes | 550 | 15 | | ● | | | | | | | | | | ● | ● | ● | | | | | 26, 27 |
| Spain, Central Pyrenees | 800 | 10 | | | ● | | | | ● | | | | | | | ● | | | | | 30, 31 |
| Spain, Eastern Pyrenees | 925 | 9 | | | ● | | | ● | ● | | | | | | ● | | ● | ● | | | 35, 36 |
| Spain, Ebro | 320 | 14 | | | | | | | ● | | | | | | | ● | | | | | 43 |
| Tunisia, Souar | 450 | - | | | | | | | | | | | | | ● | | | | | | 7 |
| Relative importance (%) Dry badlands | | | 14 | 72 | 0 | 0 | 14 | 0 | 56 | 33 | 0 | 0 | 0 | 11 | 30 | 35 | 15 | 0% | 15 | 5 | |
| Relative importance (%) Wet badlands | | | 0 | 8 | 50 | 16 | 17 | 8 | 72 | 14 | 0 | 0 | 0 | 14 | 45 | 30 | 15 | 5 | 5 | 0 | |

MAP: Mean annual precipitation; MAT: mean annual temperature; W-D: wetting-drying cycles; F-T: freeze-thaw-cycles; Sn: snow; T/S: timing/seasonality; Ant moist: antecedent moisture; R: rainfall amount; I: rainfall intensity

***References***: [1] Aucelli *et al.* (2016); [2] Bechet *et al*. (2016); [3] Breton *et al*. (2016); [4] Bollati *et al*. (2019); [5] Bosino *et al*. (2019); [6] Brandolini *et al*. (2018); [7] Bouchnack *et al*. (2009); [8] Cantón *et al*. (2001a); [9] Cantón *et al*. (2003); [10] Capolongo *et al*., (2008); [11] Castelltort (1995); [12] Clarke and Rendel (2006); [13] Clarke and Rendel (2010); [14] Crosaz and Dinger (1999); [15] Della Seta *et al*. (2009); [16] Descroix and Olivry (2002); [17] Desir and Marín (2007); [18] Desir and Marín (2013); [19] Gallart *et al*. (2013); [20] Guardià *et al*. (2000); [21] Khun and Yair (2004); [22] Khun *et al*. (2004); [23] Llena *et al*. (2020); [24] López-Tarazón *et al*. (2009); [25] López-Tarazón *et al*. (2010); [26] Martínez-Casasnovas *et al*. (2003); [27] Martínez-Casasnovas *et al*. (2004); [28] Mathys *et al*. (2003); [29] Moreno-de las Heras and Gallart (2016); [30] Nadal-Romero *et al*. (2010); [31] Nadal-Romero *et al*. (2018); [32] Piccarreta *et al*. 2006a; [33] Piccarreta *et al*. (2006b); [34] Pulice *et al*. (2013); [35] Regüés *et al*. (1995); [36] Regüés *et al*. (2000); [37] Rey (2009); [38] Ries *et al*. (2017); [39] Rodríguez-Caballero *et al*. (2014); [40] Rodríguez Caballero *et al*. (2015); [41] Rodríguez-Caballero *et al*. (2018); [42] Sadiki *et al*. (2017); [43] Sirvent *et al*. (1997); [44] Yair *et al*. (2013).

**Supplementary Table S2.** Direct, indirect and total effects among hydrological (i.e. **Supplementary Table S2.** Direct, indirect and total effects among hydrological (i.e. runoff rate [RR], runoff coefficient [RC] and maximum peak flows [Qmax] and sediment yield [SY]), and climate-drivers (rainfall amount [R], maximum rainfall intensity in 5 min [$I_5$max], 3-days antecedent rainfall [$R_{-3\ days}$], and the number of wetting-drying [W-D] and freezing cycles 10 days previous the event [Fdc], for the two study cases, El Cautivo and Araguás catchments.

| | **Direct effects** | | | | **Indirect effects** | | | | ***Total effects*** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **El Cautivo catchment** | *RR* | *RC* | *Qmax* | *SY* | *RR* | *RC* | *Qmax* | *SY* | *RR* | *RC* | *Qmax* | *SY* |
| R | 0.68 | -0.49 | 0.33 | 0.27 | 0.13 | 0.85 | 0.00 | 0.27 | 0.33 | 0.37 | 0.81 | 0.54 |
| $R_{-3days}$ | 0.00 | 0.08 | 0.02 | 0.17 | 0.01 | 0.01 | 0.00 | 0.01 | 0.02 | 0.09 | 0.00 | 0.17 |
| $I_5$max | -0.11 | 0.10 | 0.46 | 0.04 | 0.17 | 0.07 | 0.00 | 0.22 | 0.46 | 0.17 | 0.06 | 0.27 |
| RR | 0.00 | 1.05 | 0.00 | 0.15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.05 | 0.00 | 0.15 |
| Qmax | 0.38 | 0.02 | 0.00 | 0.47 | 0.00 | 0.40 | 0.00 | 0.06 | 0.38 | 0.41 | 0.00 | 0.52 |
| W-D | -0.08 | 0.00 | -0.02 | -0.02 | -0.01 | -0.09 | 0.00 | -0.02 | -0.02 | -0.09 | -0.09 | -0.04 |

| | **Direct effects** | | | | **Indirect effects** | | | | ***Total effects*** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Araguás catchment** | *RR* | *RC* | *Qmax* | *SY* | *RR* | *RC* | *Qmax* | *SY* | *RR* | *RC* | *Qmax* | *SY* |
| R | 0.67 | -0.39 | 0.46 | -0.22 | 0.17 | 0.78 | 0.00 | 0.51 | 0.84 | 0.40 | 0.46 | 0.29 |
| $R_{-3days}$ | 0.16 | 0.12 | 0.22 | -0.15 | 0.08 | 0.23 | 0.00 | 0.20 | 0.24 | 0.34 | 0.22 | 0.05 |
| $I_5$max | -0.27 | 0.05 | 0.42 | 0.23 | 0.16 | -0.09 | 0.00 | 0.20 | -0.12 | -0.03 | 0.42 | 0.43 |
| RR | 0.00 | 0.90 | 0.00 | 0.30 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.90 | 0.00 | 0.30 |
| Qmax | 0.37 | 0.05 | 0.00 | 0.56 | 0.00 | 0.33 | 0.00 | 0.11 | 0.37 | 0.39 | 0.00 | 0.68 |
| Fdc | 0.04 | 0.00 | 0.03 | 0.16 | 0.01 | 0.05 | 0.00 | 0.03 | 0.05 | 0.05 | 0.03 | 0.19 |