# Desertification in karst areas: a review

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## Abstract

Desertification in karst is an effect of climate change and not sustainable anthropogenic activities, the combination of which, however, causes the gradual loss of karst natural resources, such as soil, vegetation, and groundwater. A considerable percentage of global karst areas is found in drylands, characterized by negative water balance and scarce presence of soils. High fragility of the karst environment, and its vulnerability to land degradation and pollution because of the peculiar anisotropic setting, environmental dynamics, and of the direct connection between the surface and the subsurface, are at the origin of the severe problems deriving from desertification processes in karst. In addition to natural drivers, such as geology and topography, karst desertification is generally due to four main factors, mostly or partly related to human activity: deforestation, improper land use, groundwater overexploitation, and climate changes. Through the analysis of a collection of studies conducted in several karst territories around the world, the present paper aims to provide an overview of the processes leading to desertification risks in karst areas. Emphasizing the need to preserve these fragile environments, characterized by peculiar features and precious freshwater resources, this review summarizes the main situations at the global scale of rocky desertification in karst, at the same time providing indications for developing innovative and multi-disciplinary approaches addressed toward mitigation of the risk related to desertification in karst.

*Keywords*: Desertification, Karst, Land degradation, Human impacts, Climate change.

## 1. Introduction

Desertification represents a serious environmental problem in terms of economic losses and social issues. Since the 1977 United Nations Conference on Desertification, held in Nairobi, desertification has become one of the main challenges of both scientific and political interest. Years later, the 1994 United Nations Convention to Combat Desertification (UNCCD), held in Paris, was ratified by 160 countries; desertification was defined as “land degradation in dry, semi-arid and dry sub-humid areas, resulting from various causes, including climatic variations and human activities”. Then, the 2005 Millennium Ecosystem Assessment redefined the concept of desertification, describing it as “a result of a long-term failure to balance demand for and supply of ecosystem services in drylands”, and pointing out that desertification is caused by a decrease in land productivity due to the inability of land users to adequately respond to indirect factors, such as population pressure and globalization phenomena.

As known, drylands cover about 41% of Earth’s land surface, and about 3 billion people inhabit such difficult territories (Safriel et al., 2005; Van der Esch et al., 2017). According to their aridity index value (0.05 - 0.65), drylands are geographically classified into 4 types: hyper-arid, arid, semi-arid and dry sub-humid (UNEP, 1992).

Desertification, however, does not only regard drylands, which are particularly vulnerable to land degradation due to environmental factors such as low rainfall, low soil moisture, and poor soils, but also anthropogenic factors, such as high human demands (Safriel et al., 2005; Baartman et al., 2007; Vogt et al., 2011, Spinoni et al., 2015; Becerril-Piña & Mastachi-Loza, 2021). Generally, territories affected by desertification are characterized by negative water balance during part of or all the year, and/or by the amount of rainfall that is lower than the potential water waste (Kassas, 1995). However, drought is not the only factor involved in desertification: this phenomenon differs from the classic concept of desert (such as The Sahara or The Kalahari) because it is necessary to consider other environmental factors that could reach critical levels as a consequence of anthropogenic activities

(Yassoglou and Kosmas, 2000). Currently, around 250 million people are directly affected by desertification, and the livelihoods of roughly one billion of those people are threatened by it (UNCCD, 2007). Statistics show that about a quarter of Earth's land, corresponding to an area of over 3.6 billion hectares, is presently at risk of desertification (UNCCD, 2004).

Karst terrains are also included among the areas affected by desertification. Karst is a very fragile environment, characterized by peculiar hydrology and hydrogeology, with high physical anisotropy due to the presence of fractures and large conduits within the rock masses (White, 1990; Bakalowicz, 1995; Ford and Williams, 2007; Hartmann and Baker, 2017). A very limited presence, if not a complete absence, of runoff at the surface characterizes these environments. This is owing to the fact that water infiltrates rapidly underground through the network of fractures, conduits, and caves to produce the intricate system of karst voids (White, 2002; Palmer, 2010). In a karst environment, freshwater is typically stored underground, and karst springs represent the primary element for the development of many extremely rich ecosystems. In the latter, a karst environment is supported by nutrients and a relatively stable temperature (Kløve et al., 2011; Galassi et al, 2014). Animal species living exclusively in groundwater have become strategic indicators for good groundwater quality. In addition, the presence of available freshwater has always played a fundamental and crucial role in-the birth of civilizations and in the choice of new settlement sites throughout the history of humankind (Al Taiee, 2012; Parise et al., 2015a; Voudouris et al., 2019; Valipour et al., 2020; Madonia et al., 2023).

Human activities carried out on the surface level of karst areas may have a direct impact on the underground areas which result particularly sensitive to anthropogenic actions. Consequently, these may have severe impacts on the pristine environment (Van Beynen and Townsend, 2005; North et al., 2009; Parise et al., 2018). Damaging karst environments and the resources stored therewithin (soil, water, cave systems, biota) can occur extremely easily, also with serious consequences for the human health (Henry and Suk,2018; Padilla and Vesper, 2018), whilst restoration practices of the same are highly time consuming, expensive (Parise and Gunn, 2007), and, in many cases, fail to effectively restore the pristine situation. Therefore, the best way to protect karst is to prevent pollution. For these reasons, in 1997, the World Commission on Protected Areas of the IUCN (International Union for the Conservation of Nature and Natural Resources) recognized karst landscapes as areas that need to be protected (Watson, 1997; Gillieson et al., 2022).

One of the main threats that karstlands face is desertification; approximately 60% of karst territories is included within the afore-mentioned desertification categories, showing aridity indexes lower than or equal to 0.65 (fig.1). Contrary to what is indicated in popular literature, desertification definitely affects karst landscapes, as documented by Kranjc (2009). Studying desertification in the subtropical karst of South China, that is one of the largest exposed carbonate areas in the world, covering ~1.9 million km$^2$ (Zhang et al., 2017), Yuan (1997) introduces the term “rocky desertification” as the process leading to the loss of soil and vegetation, thereby creating landscapes with the presence of karst bedrock alone. Wang et al. (2004) point out that, since rocky desertification cannot be restricted to karst areas, the term “karst rocky desertification” is more suitable to describe rocky desertification in karst regions. They also describe this phenomenon as being caused by human activities, with the main consequences being intense soil erosion, extensive bedrock exposure, drastic soil productivity reduction, the reduction of the groundwater volume, and the appearance of a desert-like landscape. Williams (2004) also considers desertification in karst as a consequence of intensive agriculture practices leading to vegetation loss and extreme soil erosion.

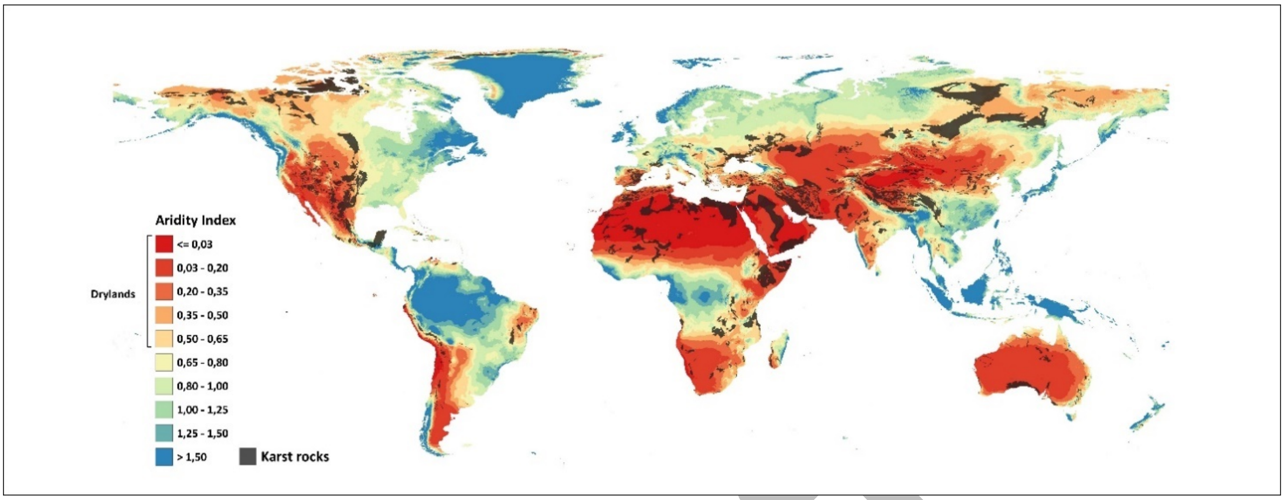

**Fig. 1 Karst distribution in drylands (modified after Chen et al., 2017; Trabucco and Zomer, 2019; Goldscheider et al., 2020).**

On the basis of the above-mentioned considerations, this paper provides an overall description of karst settings, aimed at highlighting the fragility of such an environment, the importance of the natural resources therein contained (first and foremost, groundwater), and, therefore, the need to protect karst. This is followed by a review of the scientific literature dealing with desertification in karst areas: through a categorization based upon climate and landscape types, the processes leading to desertification are examined, also taking into account the issue of climate changes. The discussion presents overall considerations about how and at what intensity desertification processes act in karst settings, as well as it remarks the location of the areas mostly at risk of desertification worldwide. Finally, the paper concludes by suggesting perspectives for future research, providing ideas for specific monitoring actions and methods in karst areas at risk of desertification.

## 2. Karst environments

Karst territories cover about 20% of the planet's dry ice-free land (Ford and Williams, 2007), with Europe having the largest distribution of karst (total area 21.8%) and a global area of 2.17 million km$^2$ (Goldscheider et al., 2020) (fig. 2). When looking at the effective surface covered by carbonate rocks in the different continents, it appears that Asia has by far the widest surface, corresponding to about 8 million of km$^2$ of exposure (fig. 2b).

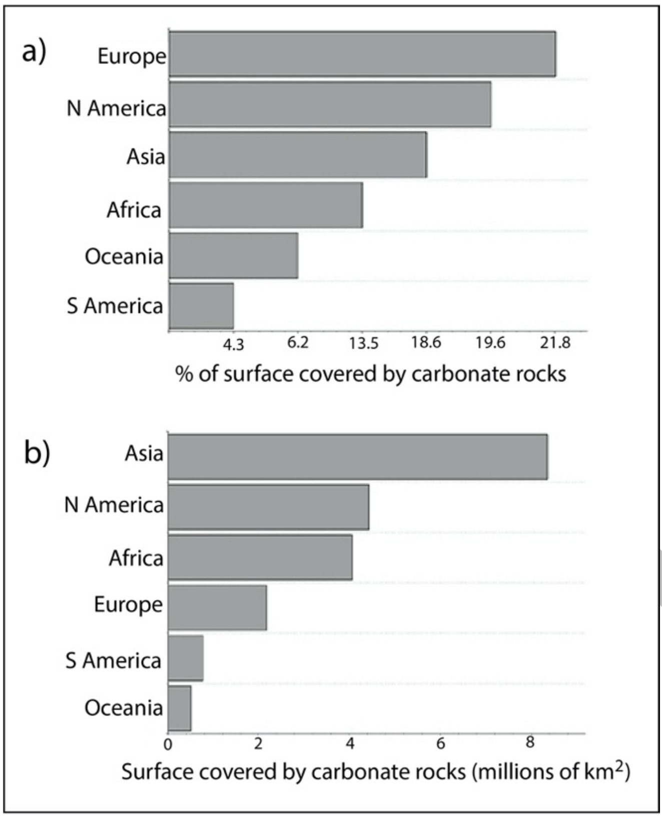

**Fig. 2 Global distribution of karst: a) percentage of continental surface covered by carbonate rocks; b) surface covered by carbonate rocks, expressed in millions of km$^2$ (data after Goldscheider et al., 2020).**

The term "karst" derives from *karra/gara*, which means stone (Ford and Williams, 2007); the first scientific studies about karst have been developed in the plateau located in the background of the Trieste Bay named "Kras" in Slovene, "Carso" in Italian and "Karst" in German (Ford and Williams, 2007; Kranjc, 2011). It is a very complex and heterogeneous environment, containing important natural resources such as underground high-quality freshwater and peculiar ecosystems with high biodiversity (Culver and Pipan, 2009; Mammola et al., 2019; Galmarini et al., 2023). The most typical features of karst terrains are represented by swallow holes, dolines, and caves, these latter hosting remarkable deposits in terms of sediments, and fossil and anthropological remains as well (Brinkmann and Parise, 2012). These make caves unique and important treasure chests able to store geological information about ancient epochs, that have been canceled at the Earth surface, removed by erosional processes and landslides, or destroyed by anthropogenic activities. In addition, caves are widely decorated by speleothems, which have become in the last decades one of the main sources of information to understand paleoclimate, and evaluate the climatic changes occurred on our planet (Lauritzen and Lundberg, 1999; Hartmann and Baker, 2017; Liu et al., 2020). In karst, the superficial landscape and underground features are essentially sculptured by both erosional (physical) and dissolutional (chemical) processes of water on soluble rocks, originating the peculiar morphological features at the surface and the presence of a huge number of underground voids. According to Klimchouk and Ford (2000), speleogenesis is defined as "the creation and evolution of organized permeability structures in a rock that have evolved as the result of dissolutional enlargement of an earlier porosity". This process is the main responsible of the creation of the underground network of voids, allowing the easy water transfer from the recharge to the outflow sites. However, karst includes features and phenomena induced by speleogenesis, but not necessary encompassed by it (Klimchouk, 2007). Speleogenesis generally consists of two main phases. The first phase is very slow, possibly lasting tens of thousands of years (Dreybrodt et al., 1996; Dreybrodt, 2004) and consists of dissolution processes leading to the formation of small-aperture fracture networks (from mm to few cm) named protoconduits, where water flows in laminar regime. The turbulent regime occurs when protoconduits reach the critical size (about 10 mm width) thanks to continuous dissolution of rocks and enlargement of voids. In this second phase the mechanical erosion enhances and speeds up the widening of fractures, thus leading to the formation of a preferential drainage network (White, 1988; De Waele et al., 2011). Subsequently, the process of conduit widening proceeds rapidly; eventually, the conduits may reach man-size dimensions, and become explorable caves (Klimchouk and Ford, 2000). Efficacy of the chemical reactions involved in dissolution is influenced by many factors, including water temperature, pH, $CO_2$ pressure, rock discontinuity, etc. These processes are very pronounced in the epikarst, representing the most superficial sector in karst terrains, directly exposed to the atmospheric agents. The epikarst (Williams, 1983, 2008) is characterized by the presence of altered and highly fractured rocks able to storage a large volume of water; once the retention threshold is exceeded, it transfers water through infiltration in the subsoil, allowing natural recharge of the karst aquifers. Epikarst plays therefore a crucial role in karst hydrogeology, being an important factor on near-surface and groundwater hydrological processes (Ford and Williams, 2007; Fu et al., 2014; Zhang et al., 2023). From the epikarst, surface water rapidly infiltrates within the discontinuities of the rock mass and flows down through fractures and swallow-holes within the vadose (non-saturated) area until reaching the phreatic, or saturated, zone (Bakalowicz, 2005). In the vadose area, underground caves and conduits of different sizes are dominant (Parise et al., 2018). Underground karst voids have an active role in the water-transfer process since they rapidly convey large quantity of water and positively contribute to the groundwater recharge. On the other hand, representing a direct link from the surface and the underground, swallow holes have to be considered potential sites of pollution since they could be used by man to dispose liquid and solid waste (fig. 3). This incorrect anthropogenic behavior poses a significant and continuous threat to the quality of groundwater and may potentially cause severe problems in terms of human health (Parise et al., 2004, 2009; Formicola et al., 2010; Day et al., 2011). As concerns hydraulic aspects of karst subsoil, the rainwater infiltrating at the surface moves down towards the unsaturated zone, where the waterflow is mainly addressed in vertical direction thanks to the gravity force; eventually, it reaches the saturated zone, where water moves mainly in horizontal direction, driven by the hydraulic gradient. Freshwater comes again at the surface at springs, discharging to the sea, lakes, or rivers (Stevanović, 2015; Liso and Parise, 2020; Eftimi et al., 2022).

**Fig. 3 Presence of liquid and solid wastes in a natural cave in Southern Italy; a) general view; b) zoom in of the area marked with the yellow rectangle in a), showing details of the presence of oil at the water surface.**

As stated above, water in karst rapidly infiltrates into the ground making difficult water accumulation at the surface, so that the water scarcity at the surface can be considered as one of the main significant superficial characters in karst settings. This could wrongly lead to consider karst poor in terms of ecosystems and biodiversity, especially in wide bare karst areas, thus making them "apparent deserts". Nevertheless, karst landscape shows a strong ecological relationship between the surface and the three-dimensional underground environment (Canedoli et al., 2022; Pisano et al., 2022). The extreme spatial heterogeneity in karst voids distribution determines the development of several habitats (i.e., cave streams, epikarst, phreatic water, springs and interstitial habitats) characterized by different chemical and biological processes (Brancelj and Culver, 2005; Bonacci et al., 2009). In particular, spring waters can sustain specific ecological habitats that are partially or totally dependent for freshwater, the Groundwater Dependent Ecosystem (GDE; Clifton and Evans, 2001; Eamus and Froend, 2006; Eamus et al., 2006, 2015; Ravbar and Pipan, 2022). Such habitats host rare and endangered species, with a high level of endemism related to the fragmentation of the subterranean habitats and the relative stability of subterranean environments (Gibert and Deharveng, 2002). However, a huge portion of underground biodiversity has yet to be described, since underground water ecosystems show lack of scientific knowledge (Ficetola et al., 2019; Manenti and Pezzoli, 2019; Galmarini et al., 2023). Biodiversity is of great value in karst systems, since specialized ecosystems and associated ecological services act in water purification and nutrient cycling, mostly carried out by microorganisms (Herman et al., 2001; Mace et al., 2012).

## 2.1 Climate and karst types

Based on their characteristics, karst types can be classified following different approaches. According to Veress (2020), karst can be grouped in two large sets, by considering its characteristics at a given time (static group) or its development (dynamic group). Following this classification, static karst includes the zonal karst subgroup, that includes karst areas in function of the specific climate. In fact, climate conditions can affect karst features and development, for example in term of climatic water balance (determining the denudation rate) that is the result of precipitation minus evapotranspiration (Ford and Williams, 2007; Goldscheider et al., 2020). In particular, diversity of karst features tends to increase the closer a zonal karst type is to the Equator, due to raising in rainfall and temperature values (Veress and Vetési-Foith, 2021). This results in higher dissolution intensity, enhanced by the high biological activity of the soil in terms of $CO_2$ production (Trudgill, 1985; Veress, 2020). In the following, this review will provide some examples about desertification and land degradation problems in three main karst types, according to climate conditions: tropical, temperate, and Mediterranean karsts (fig. 4).

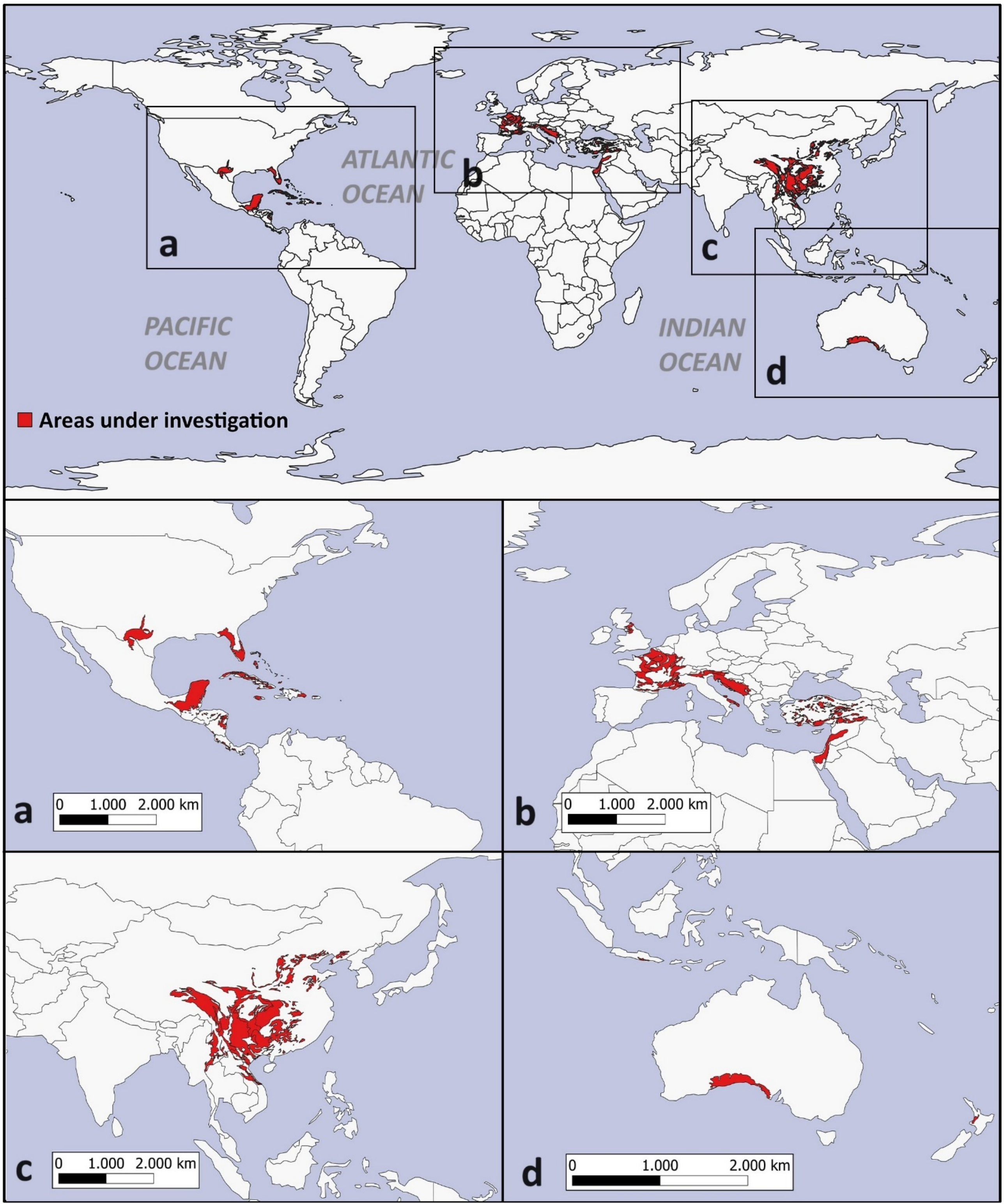

**Fig. 4 Overall view, and single zoom areas, for the karst regions examined in this review: a) Texas, Florida and Caribbean karst; b) Mediterranean Basin; c) Asian karst; d) Oceania karst.**

Tropical karst takes place under a climate characterized by large amounts of precipitation and high temperatures throughout the year. There, dissolution action on soluble rocks is the most intense on

Earth, and the significant karst denudation derives from long times of constant climatic conditions and the absence of glacial periods and young transgressions (Veress, 2020; Veress and Vetési-Foith, 2021). In tropical karst, dissolution produces typical landforms consisting in vertical hilly rocks, called “inselberg”, a German word that means “island mountains” (Khalaf, 2022). In the Chinese literature, two varieties of inselberg karst have been described, the *fengcong* and the *fenglin* karst (Zhigan, 1980; Zhu, 2005; Ford and Williams, 2007). *Fengcong* is a polygonal karst with conical hills separated by deep closed depressions (dolines, cockpits), while *fenglin* karst is composed of isolated hills separated by plains, normally formed of limestone bedrock overlain by alluvial deposits (Waltham, 2008; Veress, 2016). In temperate climate, the fluvial action is considerable in the development of karst landforms (Veress, 2016). Sinkholes and karst valleys are among the most common landform types, and deepening of the incisions around their rims or along interfluves often leaves residual or isolated hills with conical or tower-like form (White, 1990; Ford and Williams, 2007; Palmer, 2007). The presence of *uvalas*, a particular type of karst closed depression typical of the Dinaric karst, is also widespread, whose dimensions can be much wider than the largest single sinkhole (Ćalić, 2011), and that derives from coalescence of two or more individual sinkholes (Al-Halbouni et al., 2019; Margiotta et al., 2021). Eventually, in the Mediterranean area, many types of karst are present, from the Classical Karst at the border between NE Italy and Slovenia and Croatia, also including high mountains, to several different coastal karst regions, to semi-arid karst landscapes in islands and in the north African countries. Throughout all the Mediterranean basin, sinkholes of variable size and depth are typically the most common karst landform, locally marking extensively the landscape such as at Mali me Gropa (literally meaning the Mountain of the Holes) in central Albania (Andreychouk et al., 2022). Sinkholes often combine to other peculiar features represented by blind valleys, sinking streams, and *poljes* (Denizman, 2003; Dogan, 2003; Gracia et al., 2003; Parise, 2006; Pisano et al., 2020), wide and flat enclosed karstic-tectonic depressions of which several morphological and genetic varieties can be distinguished (Gams, 1978, 2005; Bonacci, 2004; Veress, 2020).

## 2.2 Karst soils

Soil formation in karst settings is closely related to the karstification processes, including factors such as time of emersion of the platforms, climate, rock type and reliefs in karstic plains and hills (Bautista et al., 2011). Rendzina is the most representative soil type in karst, composed by a silty-clay texture and characterized by a *mollic* horizon mixed with a skeletal part overlapped to the calcareous rock, with thickness ranging from 10 to 60 cm (Shishkov and Kolev, 2014). Rendzina soils are particularly vulnerable to soil erosion, since the *mollic* horizon could be easily damaged by activities such as cattle or by the use of agricultural machines, leaving the underlying calcareous bedrock exposed (Goldscheider, 2019). Soil develops in fissures, cracks and bedding planes, reaching the highest thicknesses within topographic depressions like dolines or at the footslopes. In fact, dolines may act as sediment traps, representing a potential soil organic carbon pool which is one of the most important indicators of soil quality and agronomic sustainability, impacting in other indicators of soil quality, such as plant available water capacity or infiltration (MacRae and Mehuys, 1985; Boyle et al., 1989; Hudson, 1994; Pikul and Zuzel, 1994; Reeves, 1997; Sauro et al., 2009; Pisano et al., 2022; Valjavec et al., 2022). However, karst soils are generally thin, and not very fertile; they derive from the dissolution process that brings calcium carbonate in the solution, which represents a very poor mineral basis for the formation of a soil (Williams, 2004). This results in very low rates of soil formation, making its loss a virtually irreversible process at the human time scale. In the south-western karst area of Guizhou province, in China, it has been calculated that 0.25 -7.88 million years are required to form a soil 1 m-thick (Cao et al., 2003). Karst soils are generally rich in organic matter, with high pH value and numerous species (from algae to woody plants) which favor the chemico-physical alteration processes and the rock weathering, and increase soil fertility, as well as maintain micro-biota in a state of equilibrium (Shi et al., 2022). These thin, discontinuous soils are often in direct contact with the bedrock, and therefore susceptible to erosion by precipitation runoff, especially where there is not enough plant cover (Cao et al., 2004) and/or where the natural landscape has been changed by human activities, thus predisposing it to erosion, even on gentle slopes (Pisano et al., 2022).

## 3. Main causes of karst desertification

Desertification in karst areas is naturally related to their geology and topography, that are the main factors controlling the possibility of interference with human activities. Regions with outcrops of carbonate rocks are definitely the most widespread for karst landscapes (Ford and Williams, 2007; Chen et al., 2017, 2019), followed by evaporite rocks, and, to a lesser extent, by karst developed on other rocks, such as quartzites, arenites, etc. In carbonate rocks, the rates of dissolution may differ, depending upon the purity of the limestones, and the presence of other components within the rocks; apart from such impurities, the dissolution process acts more or less with the same intensity, not causing significant differences between karst areas in limestones and in dolomites. As for evaporite rocks, the situation greatly changes, due to the much higher degree of dissolution (Dreybrodt, 2004; De Waele et al., 2017), and the lower overall strength of the rock mass. In these cases, both effects from natural causes (erosion, slope movements, sinkholes, etc.) and anthropogenic activities (quarrying, mining, degradation, etc.) can be very strong, and significantly contribute to alter the pristine landscape (Parise et al., 2004, 2008; Di Maggio et al., 2012).

Topography also plays a crucial role, which is strictly related to the karst history: when the karst landforms are very mature, and have gone through a complete stage of evolution, following the classical model by Waltham and Fookes (2003), rugged topographies such as cone and tower karst can be present. In such landscapes, the possibility of changing the landforms through a variety of human activities is very low, given the high reliefs and the rugged topography. These situations, as well as many mountainous karst areas, appear therefore to be naturally protected by human disturbances (Waltham et al., 2005; North et al., 2009; Day et al., 2011). On the other hand, in low-lands karst, especially in tropical or temperate climates, it is very easy to change the landscape for agricultural practices; for instance, filling dolines, or canceling the slight relief to produce more continuous, easy to plow and cultivate, fields are frequent actions carried out in the Mediterranean (Gams, 1987, 1993) and Caribbean (Day, 2010) karsts.

In addition to the main geological and topographical elements, and their link with human activities, desertification processes in karst environments are mainly linked to the effects of climate changes on these peculiar environments. Table 1 summarizes a collection of studies carried out over the years in which some indicators (with a significant influence on the development of possible desertification processes) have been estimated or quantified. Part of these analyzed indicators is strictly related to land use and management, such as the amount of eroded soil (Wang et al., 2004), often resulting from unsustainable agricultural practices, or the loss of vegetation caused by deforestation (Schiettecatte et al., 2008; Valjavec et al., 2022; Vilhar et al., 2022). Other activities such as quarrying and stone clearing (Gunn, 2004; Pisano et al., 2022) have deeply modified the natural karst landscape, making it more vulnerable to development of desertification phenomena. All the abovementioned aspects will be discussed and explained in detail in the following paragraphs, with the aim of emphasizing the main processes and criticalities that concern karst desertification, and provide governance suggestions to control, protect and monitoring these fragile environments.

**Table 1**

Representative studies concerning the main factors of desertification risk in karst areas.

| Indicator | Calculated amount | Reference period | Geographical area | References |
|---|---|---|---|---|
| Soil erosion | 41 Mg ha$^{-1}$ year$^{-1}$* | n.i. | Tobacco fields, Cuba | *Ronzoni et al., 1990* |
| | ~ 1m* | n.i. | Monte Baldo and Cansiglio-Cavallo massif, Venetian Fore-Alps, Italy | *Sauro, 1993* |
| | 7.5 t ha$^{-1}$ year $^{-1}$ | 33 yrs | Mundrabilla landscape, Western Australia | *Gillieson et al., 1996* |
| | 179,600 km$^2$, 40% of the total land area | n.i. | Yunnan and Guizhou Provinces, southwestern China | *Wang et al., 2004* |
| Vegetation loss | 5 Mha | 1943-1993 | Vietnam | *Ministry of Fortstry, 1995* |
| | 250,000 m$^3$* | 1930-1960 | Yucatán, Mexico | *Klepeis and Vance, 2000; Turner et al., 2001* |
| | 600,000 ha* | Last 5000 years | Taurus Mountains, Turkey | *Boydak, 2003* |
| | 95% of the total land area | n.i. | Hillsborough County, Florida | *Van Beynen et al., 2007* |
| | 14 km$^2$ | 1985-2000 | Cuyaguateje watershed, Cuba | *Schiettecatte et al., 2008* |
| | 950,000-1,380,000 m$^3$ p.a.* | 1942-1945 | Gunung Sewu, Central Java, Indonesia | *Sunkar, 2008* |
| | 160 ha | 2002-2020 | Kras Plateau, Dinaric Mountains, SW Slovenia | *Valjavec et al., 2022* |
| Water losses caused by overpumping | 125x10$^8$ m$^3$/a, 70-80% of the total karst water resources* | n.i. | North China | *Keqiang et al., 2011* |
| | Completely dry (10x10$^6$ m$^3$ until 2007) | 1963-2007 | Faria catchment, West Bank | *Hartmann et al., 2012* |
| | 2.15 mcm/year | n.i. | Islam Abad basin, Kermanshah Province, western Iran | *Taheri et al., 2016* |
| | 14.4-20.3 m$^3$/s | 1990-2014 | Ras El Ain spring, Khabour Sub-basin, Syria | *Abou Zakhem and Kattaa , 2017* |
| | 29 Mm$^3$ /a | 1961-1994 | Jinci spring in Shanxi, China | *Zhang et al., 2022* |
| Stone clearing | many hundreds kg/m$^2$ of stone removed* | n.i. | Yugoslav islands | *Gams, 1987* |
| | 40% of the total land area* | early 1970s | Cumbria county, Great Britain | *LaMoreaux et al., 1997* |
| | 30,000 ha* | 1970s-1990s | Alta Murgia National Park, Apulia, Southern Italy | *Parise and Pascali, 2003* |
| Rocky desertification | 12.96x10$^4$ km$^2$* | 1987-2005 | Southwest China | *Zeng et al., 2018* |
| Quarrying | 100,000 ha* | n.i. | Northern Jamaican karst | *Day, 2010* |
| | 200 ha* | 1976-2005 | Minervino Murge Municipality, Apulia, Southern Italy | *Parise,2010* |
| | 5267 ha | 1989-2005 | Lebanon karst | *Darwish et al., 2011* |

* estimated values

n.i.= not indicated

## 3.1 Deforestation

Deforestation is one of the most relevant factors leading to desertification, in karst areas as elsewhere (Mirzabaev et al., 2019). Forest clearing has a huge impact in increasing the tendence toward desertification in karst environments. First, it causes severe loss of vegetation and plant cover, which in turn prepares the land to be intensively attacked by the direct impact of raindrops and rainfall, particularly intense on the occasion of the first storms following the deforestation; in other words, it triggers and promotes soil erosion, due to developing major runoff, even in areas with medium to low topographic gradient. In some experimental catchments in the Waitomo karst of New Zealand, for example, it has been demonstrated that falling of trees can increase runoff by over 35% (Williams, 1993). Water erosion through rainfall mainly includes splash, gully, and rill erosion (Govers et al., 2007; McCool and Williams, 2008). Splash erosion takes place under the direct impact of raindrops, representing the first step of soil erosion by water (Li and Fang, 2016; Fernández-Raga et al., 2017), and consists in the detachment and transport of soil particles from the soil surface (Morgan, 2005; Angulo-Martínez et al., 2012). Gully erosion happens whenever runoff water accumulates and removes soil (even to considerable depths) in narrow channels (Poesen et al., 2003). One of the main causes of gully erosion is thought to be the overland flow, but gullies may also build-up due to the presence of soil pipes, that erode the underlying soil horizons, until the collapse of the tunnel (Chaplot, 2013). Rill erosion has a negligible impact on detachment of particle soils and is rather caused by concentrated flow that creates flow paths, with water depths ranging from millimeters to several centimeters (Owoputi and Stolte, 1995; Govers et al., 2007). Vegetation removal caused by forest clearing alters the hydrologic characteristics of karst terrains, where the relationship between vegetation and hydrology is particularly strong (Sarrazin et al., 2018; Vilhar et al., 2022).

In fact, in some semiarid karst shrublands, the presence of canopy areas and woody plants plays an important role in capturing the overland flow via subsurface streamflow, which is generally minimal in intercanopy areas with less vegetation cover (Wilcox et al., 2008).

After deforestation, forest interception and evapotranspiration decrease while the infiltration rate is reduced, as a result of soil erosion and compaction (Brown et al., 2005; Dung et al., 2012; Liu et al., 2015). Moreover, both flow storage capacity and resistance to overland flow become lower. When forest clearing takes place through fire, soil infiltration and surface roughness is reduced, while stream channel morphology is altered due to the loss of root strength and cohesion caused by the increasing runoff, the suspended sediment flows, occurrence of debris flows and, more generally, overland flow (Martin and Moody, 2001; Cannon et al., 2003; Shakesby and Doerr, 2006; Sheridan et al., 2011; Parise and Cannon, 2012, 2017; De Graff et al., 2013; Owens et al., 2013; Shin et al., 2013; Nyman et al., 2014, 2015). Fire may additionally cause sealing of the epikarst and a reduction in the infiltration capacity, due to stagnancy of water (Emmett and Telfer, 1994; Holland, 1994; Gillieson and Thurgate, 1999; Jiang et al., 2014). Further, deforestation causes the lowering of soil level as an effect of the decay of tree roots and the action of solar radiation, that accelerates the photo-chemical weathering of the top humus soil horizon (Gams, 1987).

In many karst areas of the Mediterranean Basin (France, Italy, the Dinaric region), deforestation began in low altitude karst plateaus earlier in the Neolithic (4000-500 BC), creating a landscape characterized by outcropping of the rocky skeleton (Gams et al., 1993), thus producing the typical bare karst, later on partly re-shaped by weathering, rainfall, and runoff waters. In the Venetian Fore-Alps karst in NE Italy, clearing of beech forests for sheep grazing and cultivation caused a constant soil erosion, which led in areas such as Monte Baldo to a complete desertification and exposition of the bare karst one meter above the general level of the remaining soil (Sauro, 1993). In some areas of the Dinaric karst, forests originally covered more than 90% of the surface, but recently their extent was much reduced, and is nowadays confined to small areas near the coast and to some dense forests inland (Kranjic, 2009). Deforestation activity in the Dinaric karst began already in prehistoric times starting from Neolithic (however with a small impact related only to coastal areas) up to dramatically increasing during the Bronze Age, due to population increase and economy necessity (Kranjc, 2012).

In tropical karst, deforestation is a major concern for several regions. In Central American and Caribbean karstlands, deforestation for agriculture and intensive farming dates back 4000 years to the pre-Hispanic Ameridian people, with a further increase related to colonial agriculture practiced by Europeans in the sixteenth century (Day, 1993). In the Yucatán karst of Mexico, large-scale deforestation, followed by significant land use impact, began in the mid-20th century, with an estimated 250,000 $m^3$ of timber removed between 1930 and 1960 (Klepeis and Vance, 2000; Turner et al., 2001). By studying karst disturbance in the Hillsborough County karst region (Florida, USA), Van Beynen and co-workers (2007) estimated that 95% of forested lands have been destroyed. During the Japanese occupation (1942-1945), in the Gunung Sewu karst region of Indonesia, teak forests underwent intensive deforestation needed for the hulls of boats and as fuel for steam locomotives during the war, significantly promoting soil loss and desertification (Sunkar, 2008). In southwestern China, deforestation has damaged the environment and ecology in several karst areas, especially during the Song (960-1279) and Yuan dynasty (1279-1368) (Chen et al., 2021). Much of the original forest was cut down, and native natural vegetation replaced with crops (Kuo et al., 2011; Li et al., 2012, 2018). The final consequence of these activities was the triggering of a serious soil loss which led to a significant increase of desert areas in southwestern China, from 912.104 $km^2$ in 1987 to 1296.104 $km^2$ in 2005 (Zeng et al., 2018; Zhang et al., 2019).

Generally, re-establishment of forest is possible in karst areas where there is a well-developed epikarst, which can retain in its fractures, voids and conduits the soil, litter, water, and nutrients (Ford and Williams, 2007; Zhang et al., 2011). In China, especially in the Southern karst of the country, several ambitious programs have been implemented since the year 2000 to restore the vegetation cover and expand the forests (Delang et al., 2015; Tong et al., 2018, 2020). Such programs have led, considering a time span of two decades, to a 19% increase in forest area (330 × $10^3$ $km^2$) in the whole China and to a major increase in growing season vegetation cover (from 69% in 1999 to 81% in 2017, occurring over ~1.4 million $km^2$) in the Southern China karst (Brandt et al., 2018; Chen et al., 2019).

Other examples of successful reforestation are represented in the Trieste Bay (where black pine woodlands cover today approximately 50 % of the region) or in some bare karst lands in Turkey, with 25.335 ha of Lebanon cedar reforested (Gams, 1993; Boydak, 2003). Vegetation restoration has a positive effect on soil infiltration rate and related soil properties, especially in arid and semi-arid regions, with its beneficial effects increasing with the age of the plantation (Kalhoro et al., 2019; Zhang et al., 2019).

## 3.2 Land use

The pristine rock karst, as well as that resulting from deforestation, can be exploited for pastures or agricultural practices, in this latter case further modifying the original karst landscape, and potentially increasing soil erosion and desertification (fig. 5). Over-grazing is one of the main reasons for the destruction of the natural vegetation in karst areas, because grazing animals such as goats or sheep inhibits the natural succession and regeneration of the forest by eating young plants (Frumkin, 1999). In addition, over-grazing processes increase soil compaction and crusting, reduce soil infiltration (and, in turn, availability of water in the soil for plants), and promote surface runoff (Bauer and Burton, 1993). Hundreds of years of over-grazing activities have led to degradation of the climax vegetation, such as the oro-Mediterranean cedar forest climax herb vegetation, that has been replaced by species which are not eaten by animals (Atalay, 1999). In the arid karst area of Nullarbor Plain (Australia), over-grazing (especially carried by rabbits) caused through years localized land degradation with severe soil loss, reduction in vegetation cover and establishment of degraded grassland with invasive plant species (Gillieson et al., 1996). In some semi-arid karst landscapes, such as the savannas of the Edwards Plateau ecological region (Texas, USA), where grazing and fires have ceased for decades an increase of woody vegetation, a phenomenon called “woody plant encroachment”, has been registered (Archer et al., 2017; Wilcox et al., 2018). As demonstrated by Leite et al. (2020), woody plant encroachment in the Edwards Plateau, carried out especially by the juniper invasion, can play an important role in groundwater recharge, enhancing the soil infiltrability. This seems not to be the same for non-karst areas such as the Post Oak Savannas (Texas, USA), where woody encroachment is causing thicketization (closing of canopies), substantially reducing the groundwater recharge (Basant et al., 2022).

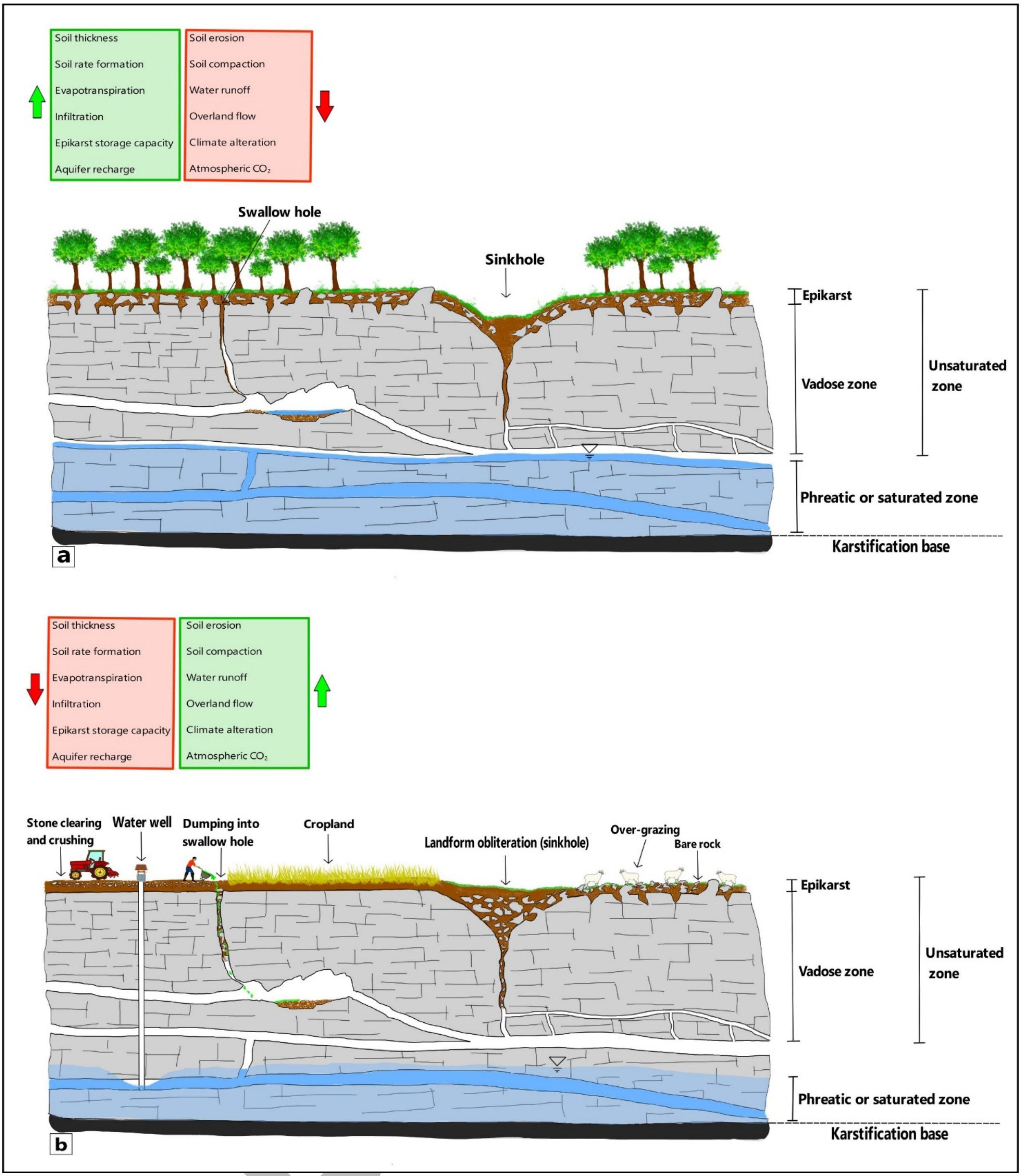

**Fig. 5 Changes in karst landscape before (a) and after (b) human activities.**

Stone clearing is a widespread practice in karst lands. It essentially consists in removing rocks from the fields (by hands, or through the use of shovels, ploughs, tractors, etc.) in order to make the soil suitable to meadows or crops. The quantity of removed stones depends on the depth of soil and the type of land use change. For example, in vineyards, where the soil needs to be stone-free for about

60 cm depth and more, the quantity of removed stones can increase up to several hundreds of kg/m$^3$ (Gams et al., 1993). When stone clearing took place through manual removal of the rocks by the farmers, the stones removed from the soil were usually collected in piles, thrown into sinkholes and depressions, or used to build some of the most typical rural architectures of many karst areas in the Mediterranean (dry-stone walls, storage houses, etc.; Aley, 2000; Laureano, 2001; Parise, 2012; Parise and Sammarco, 2015; Valipour et al., 2020). In the last decades of the 20th century, stone clearing was intensively performed thanks to the use of modern machineries, especially in Europe, due to disputable policy of subsidies from the European Communities. Machineries are able to dig the terrains down to about 2 meters, extract even huge boulders, and crushing them, in order to create a rock carpet of medium-fine grain size where to establish crops such as wheat or vineyards. These practices affected wide sectors of the Apulian karst in Southern Italy, causing destruction of the epikarst, a strong increase in surface runoff, the consequent reduction in the effective infiltration, and several geo-hydrological instability phenomena, even at low to very low topographic gradients (Giglio et al., 1996; Parise and Pascali, 2003; Canora et al., 2008; Parise, 2008; Martinotti et al., 2017) (fig. 6). Over a longer timescale, an increase in the tendence to desertification has to be registered, too, favoring soil losses through both erosion by water and wind, with this latter agent carrying away the lighter particles.

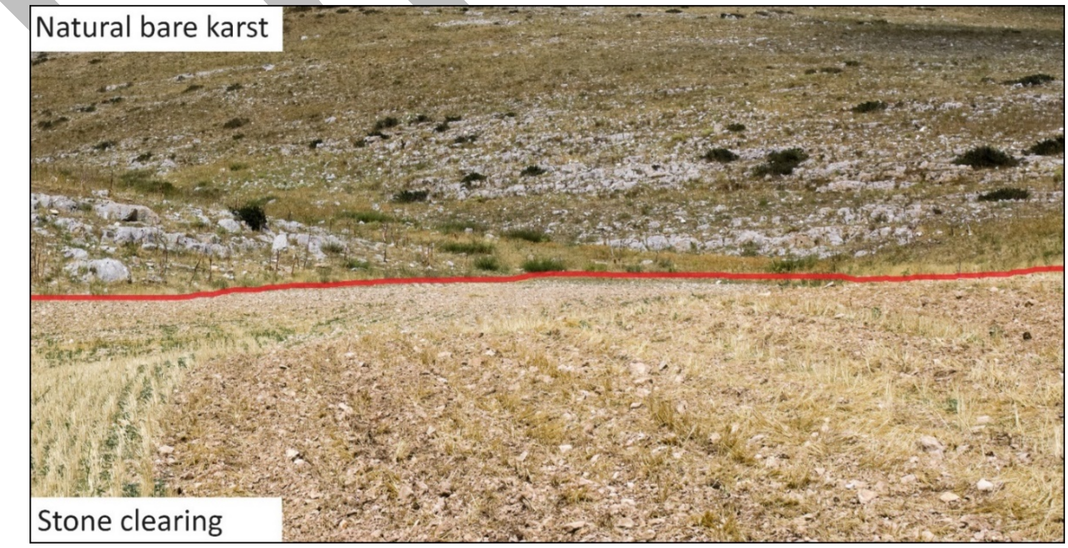

**Fig. 6 Evidence of stone clearing activities in the Alta Murgia karst of Apulia, Southern Italy.**

Land use and intensive agriculture can greatly affect runoff, soil erosion and soil structure stability. Kosmas et al. (1997) demonstrated that vineyards in hilly areas may have significant rates of runoff and sediment loss (average sediment loss 142.8 t $km^{-2}$ $yr^{-1}$), as also the areas cultivated with wheat, especially under rainfalls higher than 280 mm per year (17.6 t $kn^{-2}$ $yr^{-1}$). On karst slopes, such as over the limestone slopes of the eastern Mediterranean regions, or at steeper slopes in the Guizhou Province of China, soil loss and desertification occur more frequently due to agriculture activities (Yassoglou, 2000; Zhao and Hou, 2019). Improper crop rotation systems may also increase soil erosion, as actually happens in the Cuban karst, where more than 40% of the soils are affected by erosion, mainly as a result of intensive tobacco monoculture (MINAGRI, 2001; Schiettecatte et al., 2008). This problem is widespread in all the Caribbean karst, with a European colonial agriculture which led to clearance of the natural vegetation and degradation of soil, heavily increasing the desertification risk (León and Parise, 2009; Day, 2010). Sun et al. (2018) demonstrated that the conversion from grassland, shrubland and forest to cropland is not beneficial to soil and water conservation due to the decline of soil infiltration rate, while conversion from cropland to agroforestry could improve it. Land use change can also affect organic matter content and aggregate stability, for example through the shift from olive trees to vine cropping, which can cause a significant decrease in organic matter content and aggregate size (Kosmas et al., 1995).

### 3.3 Over-exploitation of karst water resources

Groundwater over-exploitation causes the lowering of the water surface level and the reduction of springs discharge, creating a continuous disequilibrium between the freshwater extraction and its replenishment (Tulipano, 2003; León, 2006). Over-exploitation vulnerability of karst groundwater generally depends on factors such as peculiar hydrogeological features of the aquifer, water uses, hydrological conditions and climate (Abou Zakhem and Kattaa, 2017). Karst aquifers can be described as large natural reservoirs of water, and springs discharge is related to the amount of precipitation and long-term climate changes (Chen et al., 2004; Fiorillo, 2009; Stevanović, 2015;

Olarinoye et al., 2020). According to Ford and Williams (2007), about one quarter of world's population is dependent on karst groundwater resources. Water from karst aquifers is also exploited for agricultural and industrial use, representing an important factor for local and regional economies. For example, USA is one of the major consumers of karst water, with 40% of drinking water deriving from karst aquifers (U.S. Geological Survey, 2021); further, in many areas such as the Mediterranean karst countries, large cities receive water only from karst springs (Bakalowicz et al, 2003). In China, a country with widespread presence of karst lands, overexploitation of karst water represents one of the main negative impacts for degradation of the local geo-ecology, especially in Northern China, where about 70–80% of the total karst resources (125 x $10^8$ $m^3$/year) have been exploited, leaving only 29.71 x $10^8$ $m^3$/year not used (Lu, 2007; Keqiang et al., 2011). Population growth, rising agricultural demands and economic development are globally leading to the constant depletion and stressing of groundwater resources (Wada et al., 2010). It has in fact been shown in many studies (Margat and van der Gun, 2013; Stevanovic, 2019) that irrigation water demands are much higher than the potable water supply: in detail, a large majority of the globally extracted groundwater is used for irrigation purposes, with much lesser amounts used for domestic water supply and industries. This trend, confirmed by the estimation for the 20th century by FAO–Aquastat data (2016), is going to affect severely in the future especially the arid to semi-arid regions of the world, since in those climates cropping is not possible without irrigation. In addition, the fast increase in population growth, with the consequent urbanization, will also highly increase pressure on tapped aquifers, with particular impacts on those contained in karst (Stevanović, 2019).

By interpreting satellite and land climate data, Xanke and Liesch (2022) have shown that over the period 2003-2020, groundwater storage has declined in many countries in Europe, Arabian Peninsula and North Africa, with negative trends overall in about 70% of the studied regions (fig.7; Xanke et al., 2022).

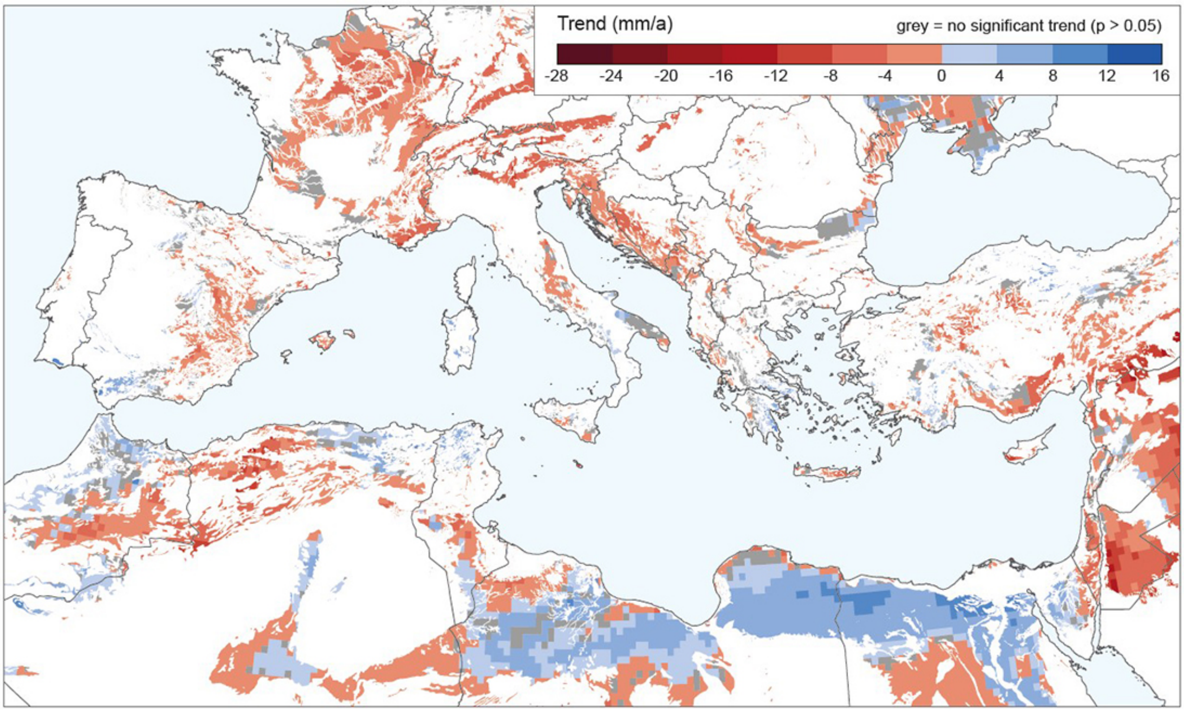

**Fig. 7 Changes in groundwater storage over the period 2003-2020 in the Euro-Mediterranean region (Xanke et al., 2022).**

Moreover, climate changes, occurring through lower precipitation and higher temperatures, will result in further reducing the groundwater recharge, especially in arid regions where karst aquifers widely extend, making the deep knowledge about the impacts of climate changes on water resources a major priority in these areas (Hartmann et al., 2012; Taylor et al., 2013; Stevanović, 2018). In coastal areas, that generally are the most urbanized and those requiring large water demands, karst aquifers is intensively exploited and under constant risk of over-exploitation (Bakalowicz, 2015; Stevanović 2019; Eftimi et al., 2023; Fiorillo et al., 2023). Further, coastal aquifer is susceptible to degradation and pollution due to its proximity to seawater, which can lead to seawater intrusion processes (Werner et al., 2012; Masciopinto and Liso, 2016). For example, in the main water structures of Apulia, and particularly in the Salento area (South Italy), the intense overexploitation caused the reduction of the freshwater volume and a widespread saline pollution due to seawater intrusion, increasing desertification and environmental degradation risk (Cotecchia et al., 2005; Margiotta and Negri, 2005; Margiotta and Parise, 2019). Over-exploitation can also lead to the collapse of sensitive part of the karst aquifer, as well as increasing the risk of natural hazards such as land subsidence and collapse sinkholes (Fiorillo, 2009; Karimi and Taheri, 2010; Gutierrez et al., 2014; Parise, 2019, 2022; Zumpano et al., 2019). In some cases, isotopic investigations may help to quantify the degree of over-exploitation of the karst aquifers. By studying tritium-based isotopic balance in two Cuban karst acquifers, León (2006) interpreted the change in the isotopic composition as an indicator of overexploitation. In fact, in certain observation boreholes, waters with no tritium, and not linked with the natural replenishment associated to the current hydrological cycle activity, has been detected during the dry season. Isotopic characterization may be also helpful to study the hydrological behaviour of karst catchments, aimed at planning karst water resource strategies in areas highly sensitive to overexploitation (Rusjan et al., 2019).

### 3.4 Climate changes

Climate changes are affecting many natural, biological and physical systems around the world, with a first quantifiable impact on the increase in temperature and sea level. Baseline scenarios expect global mean surface temperature increases in 2100 from 3.7 °C to 4.8 °C compared to pre-industrial levels, with economic and population growth being the most important drivers of increases in $CO_2$ emissions from fossil fuel combustion (IPCC, 2007). Global warming is significantly increasing natural hazards triggered by climate, with extreme events such as storms, floods, droughts, heatwaves, and wildfires, that are likely to became more frequent and intense over the years (IPCC, 2012). Climate change may have a negative impact on soil erosion mainly through changes in amount, intensity, and spatio-temporal distributions of precipitations, especially with extreme rainfall events, that are projected to increase at the end of this century (Nearing et al., 2004; IPCC, 2013; Li and Fang, 2016). Indeed, since water (along with land use) is one of the major drivers of soil erosion especially after heatwaves, extreme precipitation can affect soils through increasing rates of particle detachment by raindrop impact and runoff, which is favored by an increase soil moisture and a consequent decrease in infiltration capacity (Imeson and Lavee, 1998; Nearing et al., 2004; Morgan and Nearing, 2010; Zabaleta et al., 2014; Borrelli et al., 2020).

Human-induced climate changes are altering the hydrological cycle and exposing more people to their effects such as water-related extreme events (like floods), but also droughts, with mortality and losses much greater in poor regions with high social and infrastructure vulnerabilities (IPCC, 2023). Drylands such as desert and semi-desert are particularly affected by climate change-related droughts, due to the general lack of water availability (Middleton and Sternberg, 2013). However, other areas, like the Mediterranean basin, are exposed to natural hazards related to climate change, with an increase in droughts over the past decades, and in future climate scenarios as well (Tramblay et al., 2020). These latter scenarios indicate the decrease in Mediterranean precipitations, due to a redistribution of Earth’s rain related to the global warming, and the increase in droughts frequency expected to be 5 or 10 times greater than in the recent past (Putnam and Broecker, 2017; Zappa and Shepherd, 2017; Naumann et al., 2018). Groundwater resources will play an important role in mitigating droughts, since they can be considered less sensitive to climate change than surface water bodies, and generally have a high storage capacity (Dragoni and Sukhija, 2008; Stevanović, 2018). However, climate changes will also affect the underground freshwater availability, highly dependent on prevailing climate and associated parameters such as precipitation, temperature, and evapotranspiration, directly affecting groundwater recharge, springs discharge and, therefore, reducing the resource availability for human purposes (Green et al., 2011; Taylor et al., 2013). In addition, more frequent and longer droughts may also cause variations in water supply, especially for agricultural practices, shifting from a predominantly surface-water to a predominantly groundwater supply, increasing the stress on this last water resource (Hanson et al., 2012) (fig. 8).

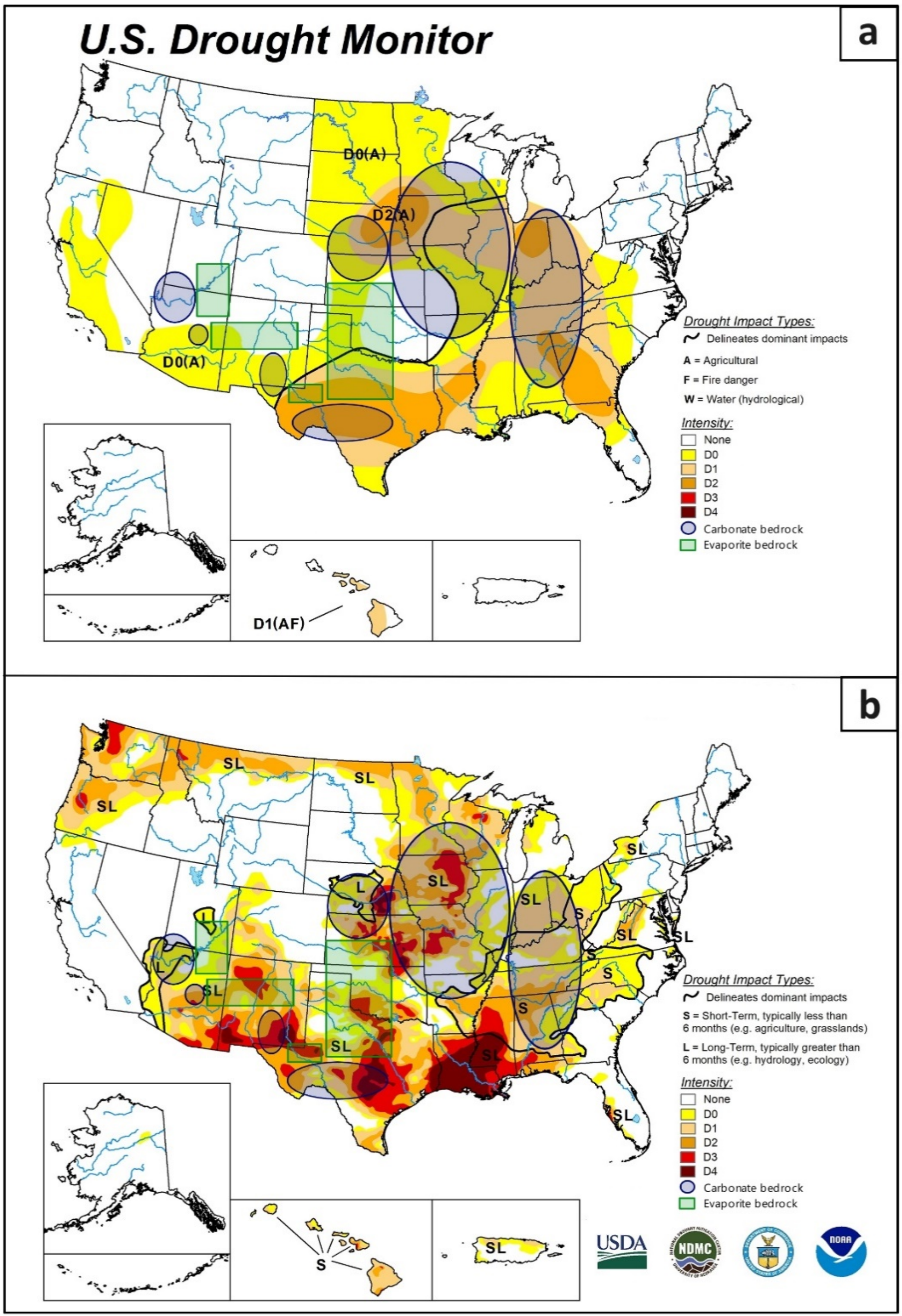

**Fig. 8 Drought maps realized in the United States: (a) monitoring in 2000, author Staff None; (b) monitoring in 2023, author Rocky Bilotta. General legend: D0= Abnormally Dry; D1=Moderate Drought; D2= Severe Drought; D3= Extreme Drought; D4= Exceptional Drought (modified after U.S. Drought Monitor). In both figures, karst lands are indicated by circles, based on the United States Geological Survey Karst Map of the Conterminous United States, 2020.**

Generally, an increase in global mean temperature is likely to increase evapotranspiration, with a potential reduction in runoff and soil water content, causing a change in groundwater level and soil moisture (Chiew and McMahon, 2002; Portmann et al., 2013; Meixner et al., 2016). Evapotranspiration changes in response to global warming are closely related to the initial subsurface water availability: in arid areas, the response of evapotranspiration to global warming is much lower than in wetlands, where water availability is largest (Condon et al., 2020).

As discussed previously, karst areas are vulnerable terrains, more sensitive to climate changes than non-karst environments. Several studies have documented that in some karst areas, such as south-west China, climate changes have resulted in extreme drought frequency in the past 50 years, accompanied by an increasing trend of minimum ground temperature in the past 60 years (Zhang et al., 2013; Lian et al., 2015). Karst groundwater resources have a global importance, but their heterogeneity and anisotropy make it extremely complex in estimating the impacts of climate changes on these aquifers (Bakalowicz, 2005; Ford and Williams, 2007; Parise et al., 2015b; Stevanović, 2019). Indeed, few studies focused on the effects of climate change on groundwater system dominated by karst flow (Hartmann et al., 2014; Morrissey et al., 2021; Leins et al., 2023). Due to the heterogeneity and the close relationship between surface and subsurface, typical of karst settings, the consequences of climate change are expected to be more evident in karst springs (Butscher and Huggenberger, 2009; Hartmann et al., 2012; Olarinoye et al., 2020). For example, longer meteorological droughts would reduce the humid period and facilitate hydrogeological crises in the aquifer, pointed out by the reduced supply of the springs (Bouabdelli et al., 2020). All stated above leads to underline a growing need to assess the intrinsic characteristics (drainage rates, permeability) of the karst aquifers and their variability in space and time, in order to protect them for future use in a scenario of climate changes (Stevanović, 2021).

## 4. Final considerations and future perspectives

Historically, karst environments are among the natural settings most exploited by humans, due to the many fundamental resources that they can host, starting from groundwater (Laureano, 2001; Valipour et al., 2020). This review shows that karst desertification has occurred (and is still occurring) in many areas of the world such as the European Mediterranean basin, south-western China, Central America, but also in other karst countries and regions as Indonesia and Australia. The presence of bare karst is one of the main common features of areas under risk of desertification; nowadays it seems to be a climate changes effect, but actually is, at least partly, the result of human activities over the millennia, too. Present-day human pressure on karst ecosystems through deforestation, not sustainable land use practices and management, and over-exploitation of water resources, has greatly enhanced desertification over the years, making such phenomena one of the most impactful and critical problems in karst (Bai et al., 2023). Past and current GIS-based methods for the desertification risk assessment, such as the MEDALUS approach (Kosmas et al., 1999), or more recent ones proposed by Santini et al. (2010) and Masoudi et al. (2018), use indicators which are inadequate for a complete assessment of desertification in karst contexts.

The future challenges for a correct evaluation of the desertification risk in karst, and for developing innovative and multi-disciplinary approaches to mitigate this problem, are represented by implementing systems that must include indices specifically dedicated to the karst environment (see Mazzei and Parise, 2018, for an overall framework) such as the Karst Disturbance Index (Van Beynen and Townsend, 2005; North et al., 2009), the Karst Sustainability Index (Van Beynen et al., 2012), or indices addressed to evaluate disturbance in karst protected areas (Angulo et al., 2013) and caves (Donato et al., 2014). These should be ideally combined with experimental models for land use and water resources predictions of future scenarios, with these latter also taking into account the impact of human withdrawals. Useful approaches for a better comprehension of desertification processes are also represented by the interpretation of satellite images, possibly integrated by specific field studies from scientists with a deep knowledge of the local karst systems, thus being able to properly identify and understand the main driving factors involved in karst desertification. Given the peculiarity of such an environment, and the variety of both superficial and underground karst landforms in function of both past and present climatic conditions, heuristic knowledge represents a fundamental tool to properly evaluate the evolution processes acting in karst terrains. On top of all the above-mentioned considerations, many variables related to global climate changes should be evaluated, too.

Further, aimed at future developments for the analysis of desertification in karst, it is necessary to obtain additional field data about its effects (i.e., loss of soil, fluctuations in the water table, changes in the ecosystems, loss in biodiversity, etc.) by carrying out multi-year experimental studies in the different seasons. This review has shown that the degree of knowledge on the matter is still low and quite sparse in the continents, with not many long-time series of data available, and often does not allow a comprehensive analysis of the involved parameters. Monitoring is essential, and should be organized in such a matter to merge data from the ground surface with those that can be collected in cave systems. This opportunity is unique in karst, thanks to availability of cavers, and to their capability to operate in the underground environment, and to monitor its characteristics. Cavers may therefore be involved for installing instruments and sensors, and downloading the related data, in active karst systems. This type of citizen science is increasingly demonstrating to be a wonderful occasion, where the experience cavers have of the subterranean world is definitely an added value for many scientific projects, as repeatedly demonstrated in a variety of recent research activities (among the others, Willenbrink, 2018; Caspari et al., 2019; Revilla-Martìn et al., 2020; Alther et al., 2021; Ragkousis et al., 2021; Arpin and Kambesis, 2022; Romano et al., 2022; Luczaj et al., 2023).

Additional actions to carry out, aimed at recovery of areas affected by desertification, result possible where the human pressure is reduced, and wherever governments are also able to apply appropriate land management strategies (LaMoreaux et al., 1997; Fleury, 2009; Prelovsek and Zupan Hajna, 2011; Angulo et al., 2013; Ravbar and Sebela, 2015; Voulvoulis et al., 2017; Vilhar et al., 2022), to implement soil conservation programs, and to promote educational campaigns addressed to inform the local communities about the vulnerability of karst environments (Bocchino et al., 2014), thus raising a more widespread knowledge about the importance of karst and of the natural resources therein contained, especially in the young generations. In this sense, the increasing awareness on the global climatic changes affecting the Earth system, and their negative effects on the planet, may work as a driver pushing the communities living in karst terrains to move back toward sustainable ways, more compatible with the natural processes, and the land managers to adopt such strategies. Protection of the remaining natural karst areas is essential, for instance, to guarantee to the future generations the possibility to have access to good-quality groundwater resources (Mirus et al., 2017; Nerantzaki and Nikolaidis, 2020), as also underlined in Goal 6 of the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015. Even though this is difficult to realize in industrialized countries, where many karst settings have been already heavily disturbed by human activities, it is still possible in many countryside karst areas in developing nations.

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