Supplementary note

Table S1. The main arid areas of the world and their more important constrains associated to aridity intensification, the main measures to drought adaptation done, their main results and the more general needs to potentiate in the future to try to avoid the negative effects of drought on degradation, food scarcity and human wellness association to aridity rise.

Region	Main hazards together with aridity rise	Main adaptation measures	Main results of adaptation measures	Future projection and main advises
Sahel	-Soil degradation -Overgrazing -Population Increase	-**Active measures of stakeholders such as**: -Agroforestry -Migration -Diversification of livestock species to more adapted to drought -Training in livestock health protection -Income diversification by work in no farm works -Reduction in herd size -Integration of livestock with crop husbandry **2/Institutional (Governmental, non-governmental of national and international level) measures**: -Mainly based in irrigation, water saving and crop development	-The stateholders food security when have adopted at least one of the adaptative measures have achieved increase the level of food security to 7-9% -The institutional measures, despite have in some cases moved great financial tools have had limited general impact in the food production and in mitigate the desertification processes.	-Sustainable drip irrigation in areas where it is effectively possible -Economy diversification and development -Political conflicts solution -Sustainable herds sizes and minimize soil and vegetation degradation. -Conservation and favoring the existence of big woody plants

South Africa	- Great population increase - Soil and vegetation degradation	-Increase of irrigation and improved seed varieties -Selection of crop species -Local markets improvement -Governmental projects to improve food security	-No success in general, observed a decrease in food security	-Recent studies advised as adequate measures to control desertification and improve food security in a realistic view include: -Control of soil erosion and adequate afforestation and reforestation -Improve water management (more resources to build infrastructures for water saving and drip irrigation implementation) and agronomic practices (no-tillage, short season crops) with great effort to promote more adequate crops in a dry scenario
MENA region	1/Israel and Arabian Peninsula rich countries -Political conflicts -Economy income dependent from petroleum (Arabian Peninsula)	-Water saving and desalinization -Water recycling -Ecosystems restoration and afforestation -Research and use of crop and wild plant varieties more resistant to drought	-High level of success	-Follow with the current level of investment in the technological application to increase water use efficiency, restore natural systems and smart agriculture.
	2/Poor countries: -Fast population increases	-Dam construction -Adaptations at the level of stakeholders	-Scarce success and maladaptation	-Decrease the dependence of rain-fed agriculture

	-Rural abandonment and migration to urban areas -Soil degradation -Political insecurity -Food scarcity and strong national income dependence of agriculture and livestock - Lack of economic resources	- Scarce Institutional-Governmental initiatives		-Apply new technologies of desalinization and water recycling -Development of smart agriculture -Increasing inter-countries cooperation -Protect the natural vegetation and restoration where possible. -Increase the adaptative capacity at the stakeholders' level
Central Asia, Gobi and North China	1/China -Great soil degradation	-Stakeholders adaptation -Great Governmental programs (water saving agriculture, reforestation, afforestation, soil protection)	- Increasing of vegetation cover and soil quality, but with different level of success depending on the region -Excessive afforestation such as in Inner Mongolia have proved to induce water scarcity.	-Use of native non-tree species should be reconsidered in several areas for restoration programs. -Continue the implementation of water saving agriculture
	2/The rest: non-China part -Great lack of data and information. -Dominance of C3 metabolism plants over C4 in natural vegetation communities -Pollution by massive use of pesticides and fertilizers	-Some recent Governmental initiatives	-Scarce success and in general increase of degradation and loss of plant cover and water sources	-Changes in cropping patters such as implementation of regenerative agriculture -Afforestation of degraded croplands -Natural vegetation restoration

	- Great drop in water resources (i.e. Aral catastrophe) in the last decades			-Improving water-use efficiency -Use of more drought resistant genotypes to drought
European Mediterranean Basin	-Crop irrigation expansion -Pollution -Some conflicts for water sources	-Diverse European Union and national initiatives with considerable budget addressed to water policy and increase water use-efficiency, to restoration and protection of biodiversity and protect the most pristine ecosystems	-Diverse level of success. The measures have helped to drought adaptation in several agriculture sectors and protect some natural valuable areas and species. However, several aspects to increase water saving and better use efficiency remains to be done	-Need to improve water sources, mainly in south Europe, - More intense and more sources should be allocated to stop desertification in some important areas of South Europe. More efficient control and laws to warrants a more smart and adequate species cultivated, mainly in South Europe.
Australia	-Very low soil nutritional capacity and specially very low concentrations of phosphorus.	-Great governmental and Commonwealth programs to invest directly in economically inversions and compensations to farmers and in infrastructures building and technological application, and also to soil restoration, reforestation and afforestation	-Some problems with inadequate and/or excessive afforestation that decrease the streams and river flows and marshes water content in some cases. But in general restoration and reforestation have had good results. -Wade trade have created more problems than it has solved	- Science integrated with stakeholder input into developing climate adaptation practices and technologies and effective adoption paths particularly to deal with climate extremes

North Brazil	- Lack of coordinated collaboration among not only Federal and States governments, but also among institutions within their own jurisdiction, create difficulties to design a drought management plan	-Governmental programs mainly addressed to improve water infrastructures, diversification of agriculture and livestock production systems, reforestation and afforestation, mitigate soil erosion and rise the access to public programs	- Several important variables have been achieved such as more stakeholders water access, more income from institutions to farmers, improvement of the articulation between distinct actors, protection of biodiversity and soil and increasing of soil organic carbon. -	-It is necessary continue working for more in integrate actions and tools for adaptation, combining technology-based solutions with in-depth knowledge of local and regional social, economic, and cultural aspects. -Invest more research and sources in proactive pre-disaster rather than reactive post-disaster events associated to aridity rise
South West of North America (only USA)	-Economical conflicts by water supply between urbanization and cropland sustainability -Population and economy expansion -Great wind erosion and dust transport	-Several state and central governmental initiatives overall in the context of infrastructure for water storing and saving, forest management and reforestation, research, water cycling and desalinization	-Despite has bracket significantly the aridity consequences the measures have been insufficient to avoid deforestation, fires, drop of water availability and the socio-economic problems linked to the rise in aridity.	-Southwest USA will also require planning, cooperation, and integration that surpass previous efforts in terms of geographic scope, jurisdictional breadth, multisectoral engagement, and the length of planning timelines -Policy measures, technical innovations and market-based solution sure that can improve water supply

				capacity and improve water demand at once. -Advance (including at technological level) is another pending question to advance in increase water sources

6.1. Africa

Three distinct regions in Africa are particularly vulnerable to the expansion of low diversity arid areas: the Sudano-Sahelian region, the Kakahari-Namib region in southern Africa, and the Mediterranean Africa. Desertification affects approximately one-third of Africa (Darkoh, 1998; Msangi, 2004). Technological, institutional and policy solutions are crucial for managing drought and climate variability in vulnerable communities across these regions (Shiferaw et al., 2014).

6.1.1 Sahel

Despite significant investments by governmental and non-governmental organizations, primarily in water-saving and irrigation projects, the results in terms of reducing vulnerability among local populations have been weak (Baba, 2014; Keita et al., 2022). For example, the ambitious "Great Green Wall" plan proposed in the 1980s to plant a continuous barrier of trees from Senegal to Djibouti has not been widely implemented (O'Connor & Ford, 2014) and would likely further damage the biodiversity through plant nonnative tree species, and planting trees in conditions where they are unlikely to survive (Hochard, 2022). Effective measures to address the consequences of aridity rise in the Sahel region need broader application, as the loss of C and nutrient stocks in plant-soil systems and desertification continue to advance (Maïga-Yaleu et al., 2015; Yang et al., 2022). Policy strategies aimed at increasing private rangeland enclosures to promote pastoralist sedentarization should also be reconsidered due to climate-induced risks and pastoral livelihood vulnerability (Berhanu & Beyene, 2015; Eliza et al., 2015).

6.1.2 South Africa

The rise in aridity in several currently arid areas is a significant concern in South Africa, stretching from Congo to the South African Republic (Nhamo et al., 2019a; 2019b). Recurring droughts, influenced by the El Niño Southern Oscillation (ENSO), continue to impact the region's people, economy, and environment. Average rainfall in the region has decreased on average by 25.6% between 1960 and 2007, and agricultural productivity is projected to decline by 15% to 50% (Davis & Vicent, 2017; Nhemachena et al., 2020).

6.1.3. MENA

Adapting to Aridity in North Africa, the Middle East, and Western Asia:

This vast region, encompassing North Africa, the northeastern part of Africa, the Middle East, and countries in western Asia, faces significant challenges due to its strong economic dependence on agriculture. Drought risk management varies across countries, presenting a complex landscape. The greatest challenge across most of these countries is the urgent need to improve drought risk management, often with inadequate or absent governmental intervention (Sowers et al., 2011; Wodon et al., 2014; Waha et al., 2017; Schilling et al., 2020; Jedd et al., 2021). The combined effects of regional population growth and warming exacerbate the situation by reducing water supplies in areas where irrigated agriculture is essential for production (Waha et al., 2017; Garrido & Rabi, 2016) (Table S1).

6.2. Central Asia, Gobi, and North China:

Central Asia has experienced a temperature increase of 0.18°C per decade during 1901–2003, twice the rate of the overall Northern Hemisphere (Chen et al., 2009). A "wet-west and dry-east" anomaly pattern, marked by changes in precipitation and aridity indices, has emerged in the expanded drylands of northern China (Chen et al., 2011; Wang et al., 2013). Modeling studies project an expansion of desert areas in Central Asia due to global warming (Ma et al., 2021).

Central Asia faces the cumulative impact of prolonged droughts, a cold climate subject to warming effects, and severe dust storms (Kurosaki et al., 2011b; Nandintsetseg & Shinoda, 2015). Winter warming also influences plant communities, and may drive desertification (Huang et al., 2012; Shinoda, 2017) (Table S1). In response, interdisciplinary initiatives like the "Applied Multi Risk Mapping of Natural Hazards for Impact Assessment" (ARMONIA, 2007) and "Integrating Dryland Disaster Science" (Shinoda, 2017) have been launched in Central Asia. These projects aim to integrate studies, identify and prevent multi-hazard risks, and develop proactive countermeasures for sustainable development (Kappes et al., 2012; Gill & Malamud, 2014). The region faces challenges from past Soviet-era policies, including massive irrigation (e.g., the Aral Sea disaster) and extensive pesticide and fertilizer use, as well as the decline of forest management systems (Lioubimtseva & Cole, 2007; Lioubimtseva & Henebry, 2009; Schlüter & Herrfahrdt-Pähle, 2011; Aleksandrova, et al., 2014). Wild woody vegetation has been proved to be reduced by aridity increases (Zou et al., 2020). However, in the last decade the Governments have initiated some programs for drought adaptation in the context of water saving, agriculture, biodiversity and forest restoration as priorities (Mustaeva & Kartayena, 2018).

China has 6.6 million km^2 of drylands that support approximately 580 million people. Despite several programs have been executed or are going on to assessment and combat desertification, degradation continues to expand and is approaching sustainable water resource limits (Yang et al., 2005; Xu et al., 2009; Feng et al., 2016; Xiao et al., 2020). Vegetation cover has increased rapidly since 2003 because of ecological recovery projects and policies (Yuan et al., 2016; Zhou et al., 2021) (Table S1). For example, the "Grain-for-Green" (GFG) program initiated in 1999 in northern Shaanxi has counteracted aridification through targeted afforestation (Li & Lu, 2015; Yuan et al., 2016). The drying trend of this region was changed by the influence of vegetation restoration promoted by the GFG program the aridity decreased by 0.14% to 2.32% per year during 2000-2012, and the mean vegetation coverage as indicated by EVI increased by 0.90% to 4.32% per year at county level. In parallel, the Northern shelterbelt program aimed to afforest northern parts China, it has had some positive partial effects diminishing storm erosion and desertification (Wang et al., 2010), despite increased precipitation in afforested regions (Li et al., 2021). The impact of human intervention, mainly by afforestation have proved to explain an 87% of greening advance in the Kubuqi Desert of Inner Mongolia (Ren et al., 2022) where, moreover, the afforestation program providing evidence of temperature smoothing (Wang et al., 2018), despite potential damage to native biodiversity (Yao et al., 2021).

6.3. European Mediterranean Basin:

EU water policy, primarily driven by the EU Water Framework Directive (WFD, 2000), emphasizes the need for robust integrated water resource management systems based on river basin planning principles

(Quevauviller, 2014). This policy aims to address drought by promoting risk management policies, enhancing drought preparedness and mitigation, and considering financial assistance tools (Wilhite et al., 2014). In recent decades, stakeholders in Southern Europe have successfully adapted to drought through measures such as transitioning to drought-resistant crop species (Costa et al., 2016; Zhao et al., 2022), restoring vegetation, reforestation, afforestation (Mechler & Kundzewicz, 2010; Pietrapertosa et al., 2018), and implementing drought monitoring and assessment (Hervás-Gámez & Delgado-Ramos, 2019) (Table S1).

At the national level in Spain, the National Indicator System for Droughts, established in 2005, has played a significant role in implementing effective measures and actions governed by the National Government (Estrela & Sancho, 2016).

While the EU's Water Framework Directive provides a comprehensive framework, challenges persist in areas such as reservoir regulation, aquifer management, and nutrient management (Hering et al., 2010). The use of aquifers in Southern Europe, while a valuable water source, faces issues like overexploitation (causing aquafer depletion), pollution, and salinization near coastal areas that necessitate proper legislation and assessment (Estrela & Vargas, 2011). Drought adaptation has mainly included selecting more drought-resistant plant and livestock genotypes, adjusting planting seasons, and shifting crops northward (Iglesias et al., 2011a; Rodrigo-Comino et al., 2021) (Table S1).

6.4 Australia

Due to the region's socio-economic and technical capabilities and its integration into the Australian state and commonwealth, stakeholders have demonstrated high awareness and effective tools to mitigate the multifaceted impacts of drought (Kiem & Austin, 2013) (Table S1). Consequently, various governmental programs and plans have been executed to prevent drought impacts, conserve water, support afforestation, enhance water use efficiency, and provide economic compensation to affected stakeholders and enterprises (Herron et al., 2002; Kiem & Austin, 2013).

Enormous financial resources from Commonwealth and State Governments, communities, and individuals have been invested in drought mitigation. For instance, during the millennium drought (2001-2009), the cost of mitigating losses, replacing ecosystem services, and adapting to new ecosystem equilibria in the Murray-Darling river basin alone was estimated at $810 million (Banerjee et al., 2013). Water trade strategies have shown that determining water supply prices for various activities can be challenging, with solutions to one problem sometimes creating larger ones (Edwards et al., 2008; Kiem, 2013) (Table S1). Notably, infrastructure projects focusing on water conservation at various levels have achieved success (Kiem, 2013), along with ecosystem restoration and reforestation efforts (Hobbs et al., 2016). In the Melbourne region, the development of water harvesting systems from stormwater and water recycling has substantially increased water supply capacity for urban and agricultural use. However, sustaining these improvements amid growing consumption and increasing aridity remains a challenge (Low et al., 2015). While successful initiatives have been implemented, there is still much to learn about effectively addressing aridity in this economically powerful country. Integrating science and technology into stakeholders' daily practices has been identified as a key approach to advancing drought adaptation (Howden et al., 2014).

6.5 North Brazil

The Semi-Arid region of Brazil (SAB) faces significant aridity challenges. During the period 1973-2001 (P1), governmental policies focused on "combatting drought and its effects." In contrast, the period 2002-2016 (P2) adopted the concept of "coexistence with semi-aridity" as the guiding policy principle. A comparative analysis of 10 territories within SAB showed substantial improvements during both periods, including increased access to water infrastructure (+33%), diversification of production systems (Livestock +36%; Crops +61%), enhanced political organizing (+24%), and better access to public programs (+29%) (Table S1). Measures aligned with the concept of coexistence with aridity, such as creating resource reserves for drought periods, reforestation, afforestation, and improved collaboration among diverse actors, have been particularly successful. Shade from trees has protected crops from heat and wind, increased productivity, preserved water sources, and enhanced biodiversity (Altieri & Nichols, 2017). Innovations like Family Seed Reserves (FSR) and Community Seed Banks (CSB) have been instrumental (Almeida & Cordeiro, 2001). Soil conservation practices, including diffusion and infiltration canals, terraces, stone barriers, and living barriers of cacti, have regulated water flow and increased water infiltration, reducing soil erosion by 80% (Pérez-Marin et al., 2007) and boosting soil organic matter levels by 25-150% (Menezes et al., 2002; Tiessen et al., 2003).

Integrated water resources management, especially for rain-fed agriculture, remains essential (Campos, 2015). More proactive, knowledge-based actions, including seasonal climate forecasts and studies on drought impacts, are needed to address contemporary environmental risks and prevent irreversible climate change (Marengo et al., 2021) (Table S1).

6.6. South West North America

Over the past few decades, droughts in the Southwestern USA have been characterized by exceptionally high temperatures (MacDonald, 2010). Unfortunately, the future doesn't look promising, as climate models predict increased aridity and more severe droughts throughout the 21st century. Additionally, there will likely be a decrease in rainfall frequency but an increase in intensity, which can exacerbate soil erosion (Archer & Predick, 2023).

Significant changes have already been observed in the timing of snowmelt in the Southwest USA (Fritze et al., 2011). Since snowmelt contributes significantly to the region's stream flows (30% to 75% depending on the basin), a reduction in total snowpack has significant economic consequences, and especially since irrigation agriculture heavily relies on groundwater resources (Hunter et al., 2006). Unfortunately, overexploitation of groundwater has been a constant issue in the region. Furthermore, aquifer drawdown and saltwater intrusion in the Phoenix area limit further groundwater extraction (Gober, 2010; MacDonald, 2007).

Regional population growth and economic expansion are projected to intensify domestic water demand, which is expected to increase even without additional transfers from rivers (Table S1). Transferring water from agriculture to meet domestic demands raises concerns about rural sustainability and food security (MacDonald, 2010; Steele et al., 2010).

In dryland areas of North America, desertification resulting from increased aridity is strongly linked to wind erosion and dust transport (Duniway et al., 2019) (Table S1). While dryland soils are generally stable when intact, disturbances such as fires, livestock grazing, and off-highway vehicle use can dramatically increase wind erosion, sometimes by as much as 40-fold. Innovative approaches to dryland restoration that minimize surface disturbance may help achieve restoration goals while limiting wind erosion risks. Addressing this complex issue requires multidisciplinary and multijurisdictional approaches and perspectives (Duniway et al., 2019). However, research on native species like *Pinus ponderosa* has shown promise in breeding and selecting drought-resistant genotypes (Kolb et al., 2016).

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