

Science
for Public
Policy

Drought

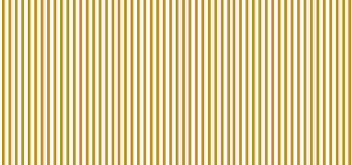
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General State Administration publications catalogue: <https://cpage.mpr.gob.es> CSIC

EDITORIAL CSIC: <http://editorial.csic.es> (email: publ@csic.es)



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NIPO: 155-24-096-4

e-NIPO: 155-24-097-X

Legal deposit: M-11808-2024

Non-commercial edition

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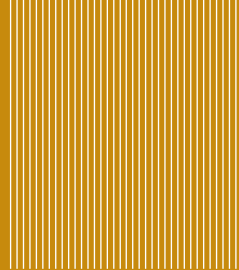
Fabiola Barraclough

Printed in Spain

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THE CSIC's functions include informing, assisting and advising public and private entities on science and technology, as stated in article 5 of its Articles of Association. Undertaking this task, we present the report, *Droughts*, from the Science for Public Policy series, which is addressed to the European Commission, public administrations and society in general. This report explains basic concepts related to droughts, outlines their impacts on agriculture, ecosystems and society. Finally, we present the most important research projects underway at the CSIC to address the management of water deficits.

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Drought



DROUGHT is one of the major natural hazards affecting our planet. It affects both natural ecosystems and societies in developed and developing countries, and interacts with climate change. When people think of weather-related natural disasters, they usually refer to tropical cyclones, floods, tornadoes or other phenomena, but they do not often think of drought, despite the fact that drought has historically been the most lethal weather phenomenon and continues to kill tens of thousands of people around the world today.

Drought has been the cause of human migration, war and even the disappearance of civilisations. Few natural phenomena can compare with the devastation caused by drought. Its surface area often exceeds that of any other natural disaster and its effects reach the entire ecosystem, with dying forests, parched grasslands and, in the most extreme cases, desertification and soil erosion. These effects are compounded by the dreaded forest fires, which spread more rapidly with dry vegetation. Animals die of thirst or starvation for lack of food, and some villages see their way of life disappear as they are unable to cope with drought. They will have to choose to either starve or migrate. Lack of water can lead to desertification and poverty for years to come. Even in countries with healthy economies, drought has very negative impacts that ripple through the socio-economic system, leading to sectoral and territorial conflicts.

Therefore, previous experiences in drought management at the regional, national or supranational level can contribute to limiting risk and devising efficient strategies to cope with this natural disaster. Thus, this report, in addition to delving into the characteristics, types and consequences of drought, presents the contributions made by researchers at the CSIC in their endeavour to solve both the global and regional challenges posed by drought.

11.

What is drought?

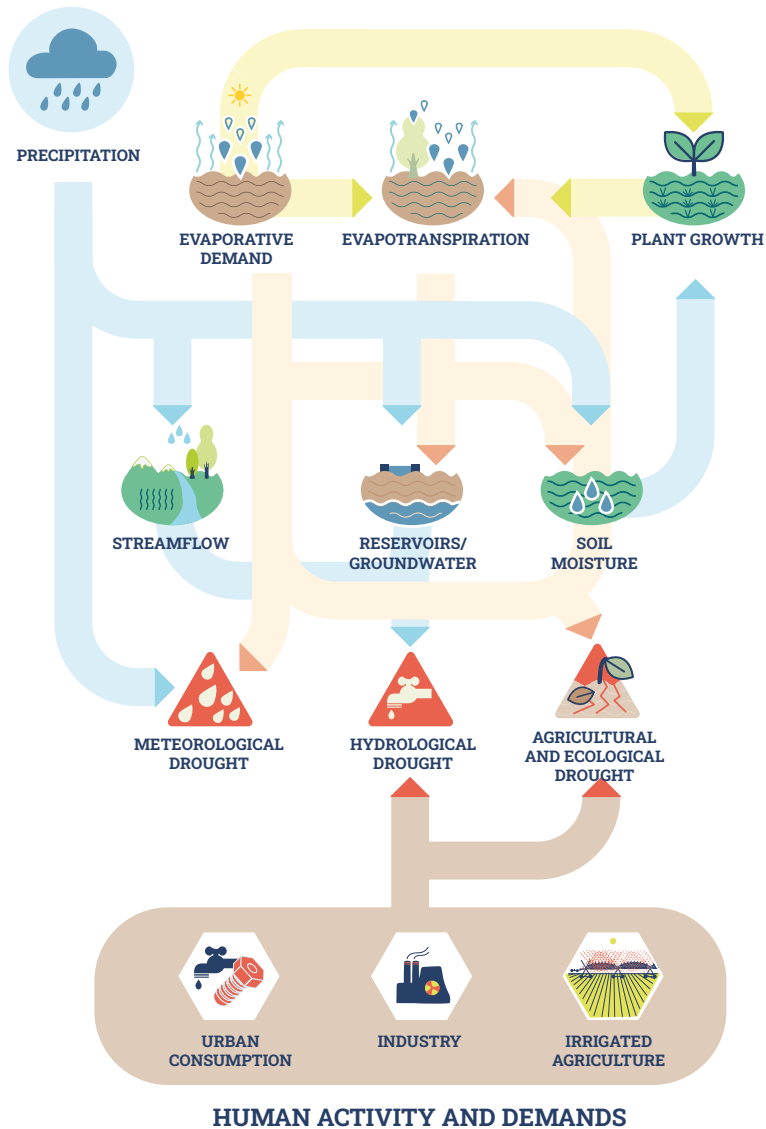
DROUGHT is an anomalous situation in which there is a deficit in water availability, causing negative impacts on crops, ecosystems and society as a whole. It is very difficult to establish fixed thresholds of duration or intensity to define drought. In some cases it appears suddenly, while in others it develops over a long period of time. It is also difficult to assess the degree of water deficit, as drought can occur in different areas (agricultural, hydrological, ecological, etc.), each with its own characteristics.

Drought should be distinguished from other related concepts, such as aridity, which refers to the average humidity conditions of a region. There is also frequent confusion between drought and the dry season, which occurs regularly every year in certain climates and does not represent an anomaly, such as summer in the Mediterranean climate. Finally, water scarcity refers to a chronic situation of lack of water resources as a result of an excessive demand compared to available water resources.

Drought is therefore a very complex phenomenon; although it has a fundamentally hydro-climatic origin in which precipitation deficit plays a preponderant role, it is very difficult to quantify. In fact, it is not possible to use a single variable to characterise drought, as there are multiple interactions between climatic conditions, soil, vegetation, surface water and groundwater hydrology.

In addition, human activity can affect the intensification and spatial and temporal spread of drought, as land management, land use, water resource regulation and water demands can reduce or increase its severity. For example, the development of intensive and water-inefficient irrigated agriculture will put significant pressure on water resources and may increase the severity of drought downstream.

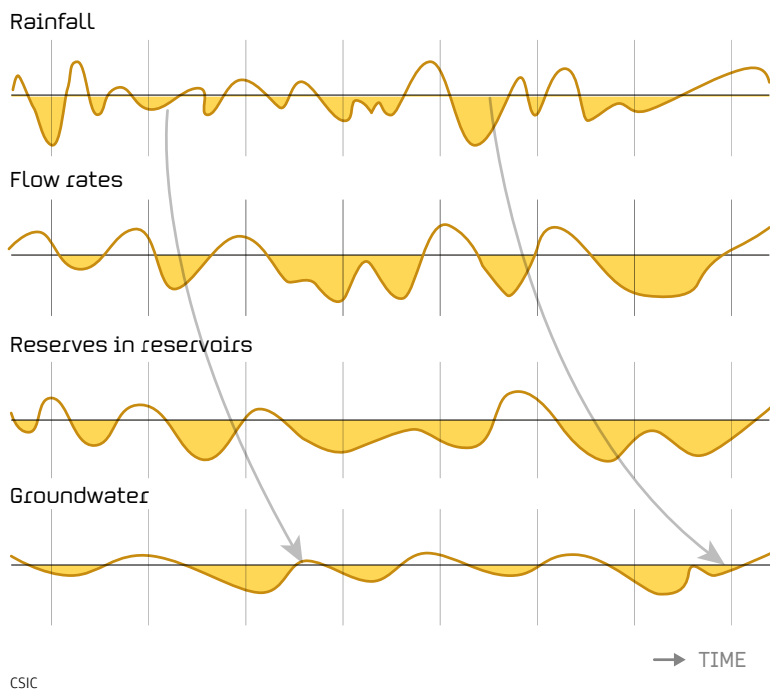
Figure 1.1 Components of drought



Climate, ecological and human interactions leading to drought. / IRENE CUESTA. MODIFIED FROM THE SIXTH PROGRESS REPORT OF THE UNITED NATIONS INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

Drought is multidimensional in nature, occurring in different socio-economic or ecological systems, and in different phases of the hydrological cycle, so there are different types of drought: i) meteorological drought, in which rainfall is below average values, and which can be aggravated by an increased demand for water by the atmosphere; ii) agricultural drought is characterised by a lack of soil moisture necessary for crop development, resulting in crop reductions or losses; ecological or environmental drought is caused by a lack of available water for natural vegetation and is a key factor in the impact on ecosystems; iii) hydrological drought is related to a prolonged decline in different sources of water resources, such as flows, reservoirs and groundwater; iv) socio-economic drought is when it affects societies and economies in the form of water restrictions, low agricultural productivity, higher energy prices and other indirect effects.

All these types of drought usually occur together, and it is usually the meteorological drought that gives rise to the others. However, this causality between droughts depends on multiple factors, including the water needs of natural vegetation and crops, the state of conservation of ecosystems, the characteristics of river basins, and the capacity to regulate and manage water resources. In addition, there are delays between meteorological droughts and other types of droughts occurring, which are usually short in the case of agricultural droughts and longer in the case of hydrological droughts, especially when groundwater reserves or high-capacity reservoirs are affected.

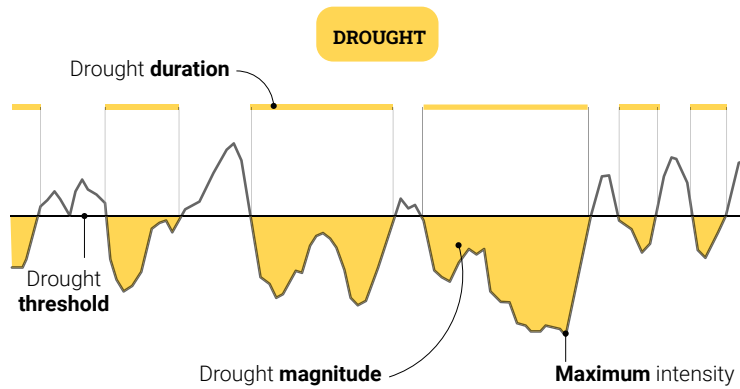
Figure 1.2 From meteorological to hydrological drought

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Indicators, generated from variables, are used to study and monitor drought. These variables are often climatic, but also hydrological (soil moisture, reservoir storage capacity, river flow, groundwater, etc.), and more recently plant growth data, measured from satellite images. Using these indices, it is possible to identify a drought event in terms of its main components: duration, total magnitude of the deficit, average intensity and surface extent. Drought severity is often referred to as a non-quantitative value that brings together all these characteristics of the phenomenon and its associated impacts. Thus, very long-lasting droughts, of considerable importance and affecting large territories are often referred to as mega-droughts. Moreover, the speed with which a drought occurs is important. Mostly, they require long periods with little precipitation, although there are also droughts characterised by a rapid onset, known as flash droughts, which can have very significant impacts on agriculture and ecosystems.

Figure 1.3 Magnitude, duration and intensity of the drought



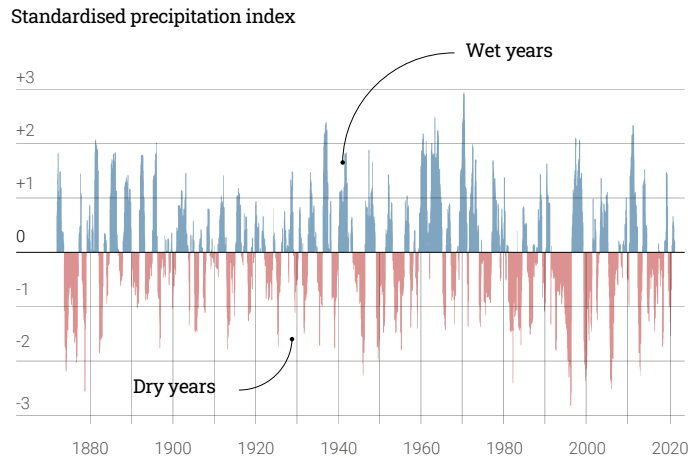
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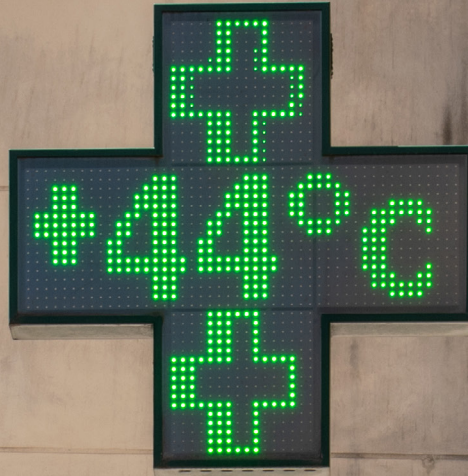
The human footprint: climate change and overexploitation

DROUGHT is a phenomenon that has been recurrently linked to natural climate variability, controlled by the atmospheric circulation and inter-regional moisture transport. In recent decades, very severe droughts have occurred in different world regions, suggesting a link to climate change. However, the analysis of the precipitation series of more than one hundred years available throughout the world shows little change in the occurrence of particularly severe precipitation. The human footprint: climate change and overexploitation deficits. In fact, in Spain, episodes such as those of the first decades of the 20th century are not uncommon over the last 170 years.

Figure 1.4 Trends in drought over time



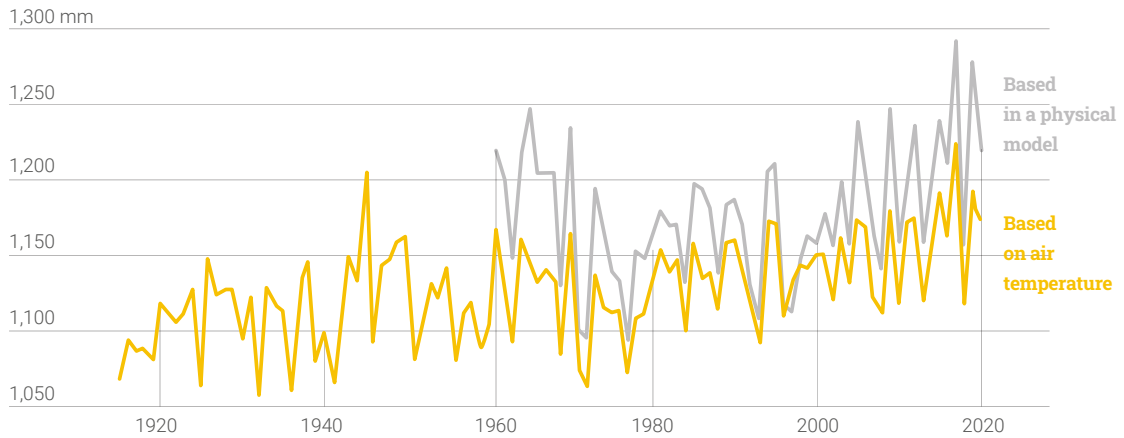
Trends in the average standardised precipitation index for Spain between 1870 and 2020. / csic



Changes in rainfall lack statistical significance; however, recent decades have witnessed a clear rise in atmospheric evaporative demand

21% de plastique en moins
que les bouteilles 1.5l

Figure 1.4 Rising atmospheric evaporative demand



Trends in average atmospheric evaporative demand for Spain from 1916 to 2020. Two methods are used, the more robust being the physical model, for which the necessary data have been available since 1961. / csic

However, in addition to precipitation deficits, there are other climatic factors that influence drought, the main one being atmospheric evaporative demand, which depends on air temperature, relative humidity, wind speed and solar radiation. During periods of precipitation deficit, high atmospheric demand increases evaporative water loss from soils, vegetation and reservoirs, and increases stress on vegetation and crops. Thus, although changes in precipitation are insignificant, there has been a marked increase in atmospheric evaporative demand in recent decades due to the increase in average temperature.

The increase in atmospheric evaporative demand on a global scale has been more than 50 mm since the 1980s, from 1,240 mm/year to 1,300 mm/year, on average. In some regions this increase has been much greater. This is the case in Spain, where annual demand has increased by more than 120 mm since 1960 and has reached 1,200 mm/year on average in the last decade.

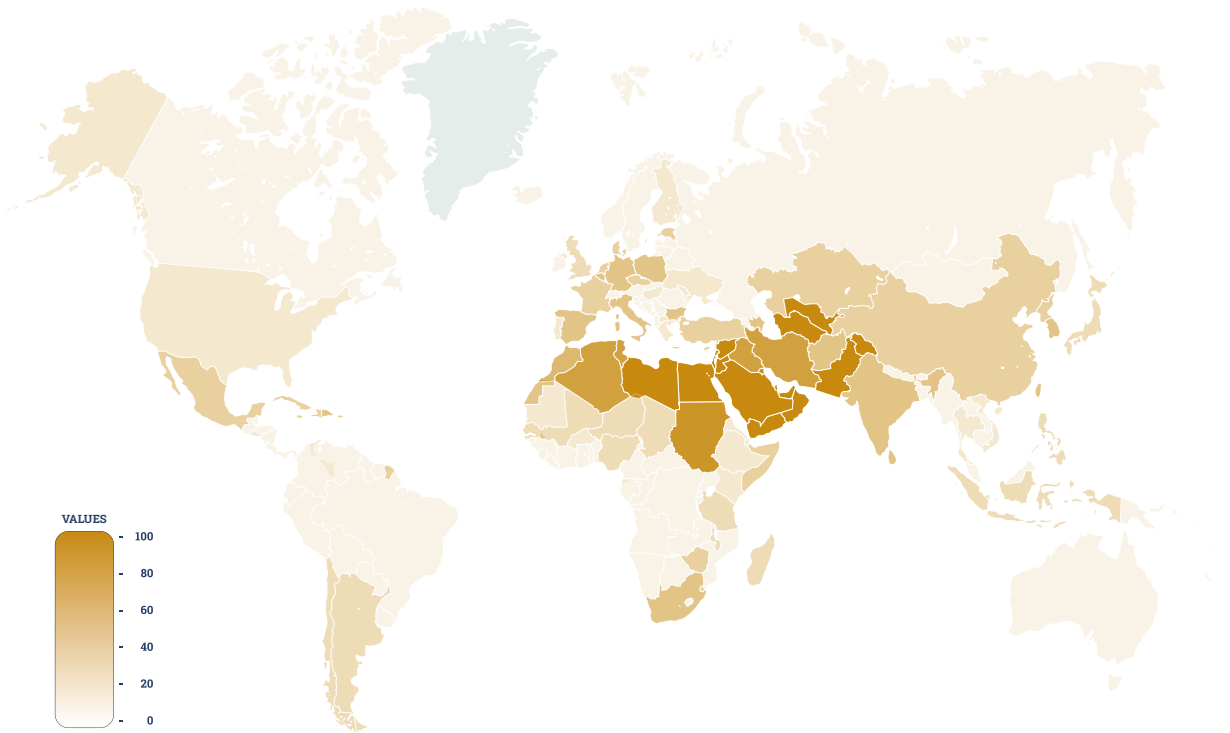


This means that in periods of low water availability, the severity of drought increases, especially in the case of agricultural and ecological droughts.

Beyond climatic factors, water-resource management is another key element in understanding the evolution and impact of drought. Nowadays, there are about 36,000 large dams in the world, three times more than in 1960. In parallel, global water use has increased from 2,000 km³ to 4,000 km³ annually due to population growth, economic development and changing consumption patterns. If we consider trends in the world population, however, water availability per capita has dropped by half in the same period. This information is a good indicator of the increasing pressure on global water resources. In Europe, North America and Asia, the impact of hydrological droughts has increased by up to 500% and their incidence by 27% over the last decades, mainly due to increasing water consumption.

In Spain, the increase in the frequency and severity of hydrological droughts has been very notable. Many basins draining the Mediterranean show flow losses of more than 50% since the 1960s, a percentage much higher than the changes attributable to climate change. In addition, there has been an increase in the forested area in headwater areas and in the irrigated area from 1.5 million hectares in 1950 to more than 3.5 million hectares today. River-basin regulation capacity in Spain has increased considerably in the above-mentioned period, from less than 15,000 hm³ to over 55,000 hm³; nonetheless, irrigation restrictions are still implemented during dry years. This situation is due to the enormous water demand by these farms, leading to chronic water resource availability deficits in most Mediterranean basins in Spain.

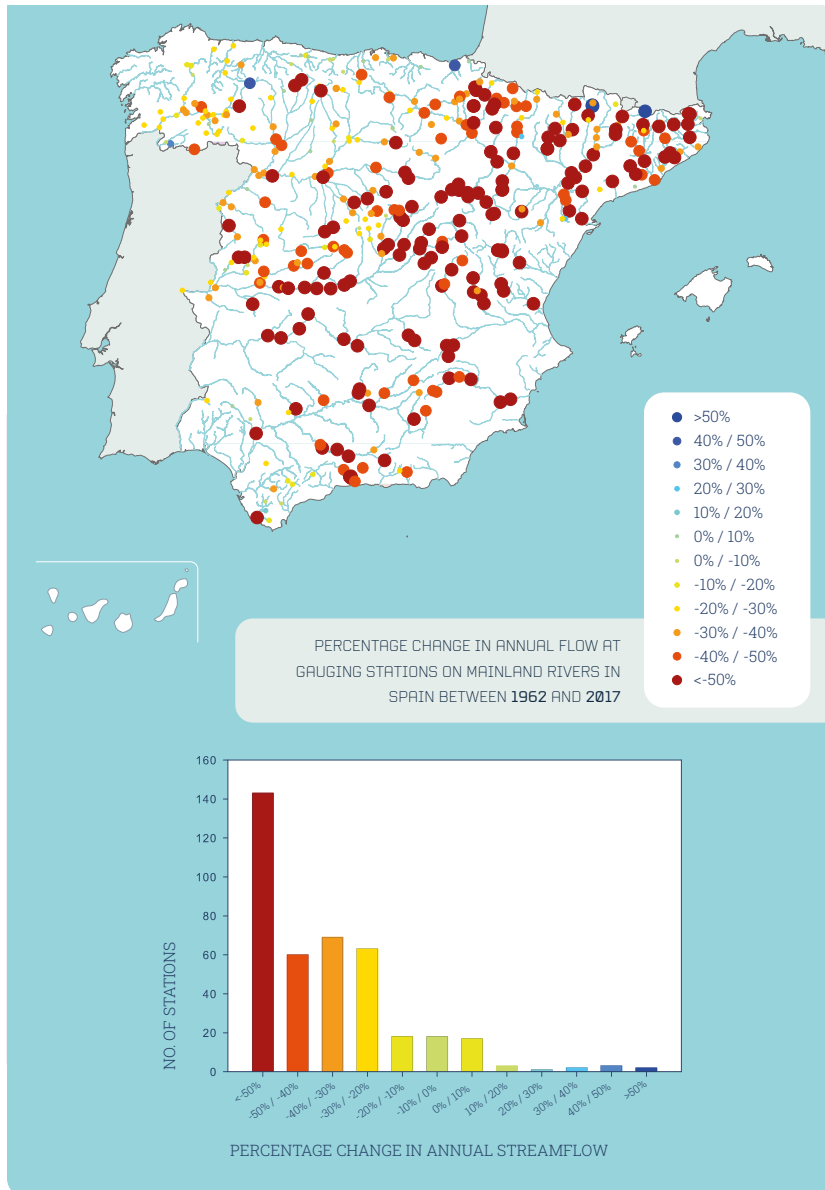
Figure 1.5 Map of the exploitation rate of water resources in the world



The water resources exploitation index is the ratio between water consumption and annual renewable water resources. Values above 50% indicate a risk of chronic water scarcity conditions, as there is not enough margin to counteract climate variability and drought. / CSIC

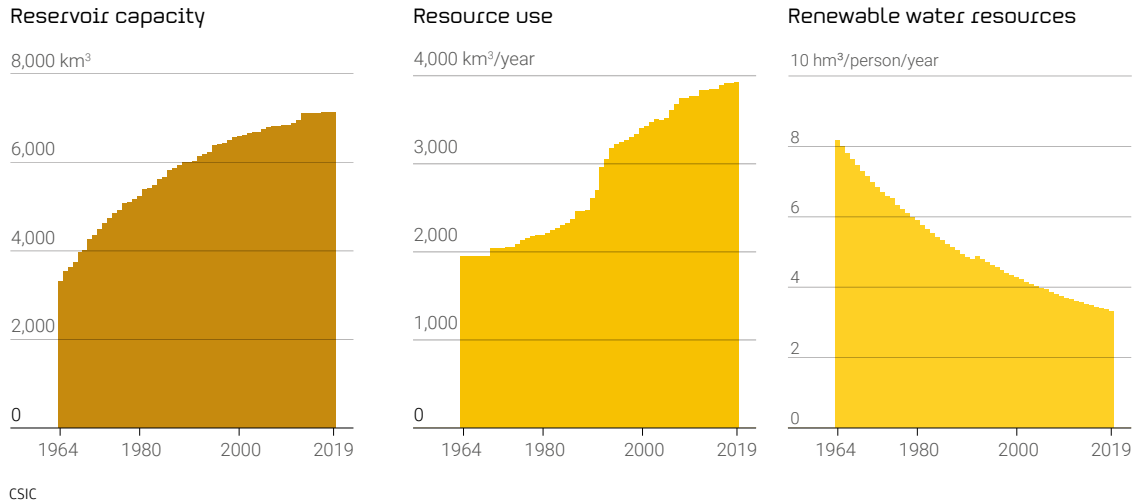
Looking ahead, there are major uncertainties in determining the evolution of droughts. The most recent model estimates simulate different climate change scenarios and suggest contrasting evolution depending on the variables being analysed. In the case of precipitation projections, models point to more frequent and longer-lasting precipitation deficits in some regions such as Central America, South Africa, Western Australia, Chile and the Mediterranean region, including Spain.

Figure 1.6 The annual streamflow has decreased in most rivers in mainland Spain



IRENE CUESTA (CSIC)

Figure 1.7 Trends in the world's water resources



However, irrespective of these model projections, it should be noted that even in regions where precipitation is expected to increase, some periods of precipitation deficits will be recorded. When such shortages occur, the atmospheric evaporative demand due to rising temperatures will lead to a significant increase in water stress on vegetation and crops, and to reduced surface water resources. In other words, higher temperatures will lead to higher than average atmospheric evaporative demand, resulting in more severe droughts, greater stress on vegetation and less availability of water resources, especially in dry climate regions.

13.

Impacts of drought

THERE is an urgent need to quantify the impacts of drought, although there is hardly any information available. This is essential to assess and mitigate the risks arising from this phenomenon, which despite affecting countries and regions with very different income levels, has dire consequences for developing countries. According to the United Nations, between 1970 and 2019, drought was the natural phenomenon that caused the highest number of deaths, some 650,000. In addition, it is estimated that around 55 million people are affected by drought each year, leading to worrying humanitarian crises.

In developed countries, the impacts of drought are mainly associated with economic losses, which can be very large. It is estimated that approximately €9 billion is lost in the European Union (EU) and US\$6.4 billion in the United States. In the EU, the highest losses occur in Spain (€1.5 billion/year), Italy (€ 1.4 billion/year) and France (€ 1.2 billion/year). Depending on the region, impacts in Europe are mainly concentrated in agriculture (39%-60%), followed by the energy sector (22%-48%) and urban supplies (9%-20%). The impacts are particularly severe in regions where agriculture or livestock farming are of major economic importance. In short, drought has a cross-cutting effect on ecosystems and biodiversity, on agricultural and livestock activity and, consequently, on the economy and society.

Impacts on agriculture, livestock and food production

Drought reduces plant growth and yield mainly due to loss of cell turgor, reduced CO₂ assimilation, oxidative stress and nutritional imbalance. This is a serious problem for crop productivity, as water is key to a multitude of processes in plants that determine their growth and development. These difficult issues lead to a decrease in food production, which, in turn, leads to higher commodity prices and loss of income for farmers.



Drought-stricken maize field. / iStock

Drought affects plants in both roots and leaves due to lack of water in the soil and high atmospheric demand. In the short term, plants respond to the lack of water by regulating various processes, such as stomatal closure, water transport or turgor pressure. However, if drought persists, plants make adjustments in root growth and leaf area through complex molecular, cellular and physiological responses that seek to save water and adapt to drought.

The impact of drought depends on the time it occurs during the plant development cycle and will, therefore, have a different impact on food production. During germination and the seedling becoming established, drought delays development and limits growth. In the vegetative stage, it reduces plant development and alters plant morphology, affecting the quality of crops such as leafy vegetables. During reproduction, it causes flower and grain abortion, reducing fruit and seed formation. In addition to these direct effects, drought increases the incidence of pests and diseases in crops, as weakened plants are more susceptible to such damage. It also reduces the activity of beneficial micro-organisms in the soil, which impacts on the availability of nutrients to plants, leading to a long-term decline in soil fertility and decreasing yields.



The quality and quantity of agricultural production is affected by the drought. / iStock



Drought also directly affects livestock by reducing the availability of pasture and compromising the production of key feed crops (maize, soybean, wheat, alfalfa, etc.), making livestock nutrition difficult. This has important economic and nutritional implications for the livestock industry. In addition, drought impacts on the practice of transhumance, a traditional grazing system that depends on access to water supply points during the seasonal movements of herds. These impacts make movement difficult and can lead to the concentration of animals in limited areas, increasing pressure on available resources and contributing to soil degradation.

Cow grazing in a drought-stricken field. This reduces the quality of feed for livestock. / ISTOCK



Aerial view of the Santa Olalla lagoon in Doñana on 2nd September 2022, affected by drought and overexploitation.
/ ESTACIÓN BIOLÓGICA DE DOÑANA

Hydrological impacts

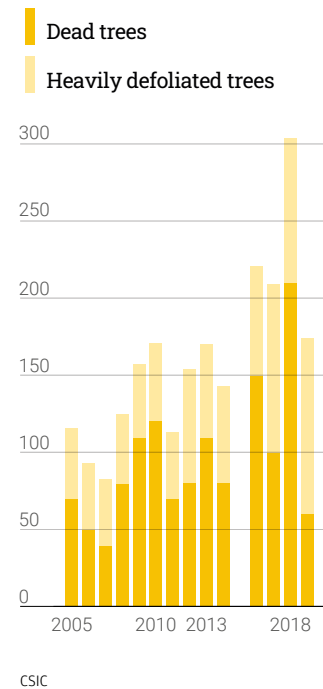
Drought can significantly alter the water cycle: it reduces the availability of water resources and influences water quality. Scarcity of water resources has direct consequences on the ecosystems associated with water bodies, but also affects irrigation, drinking water supply, hydropower generation and industrial activities, all of which have a negative impact on the economy and society as a whole.

In addition, drought causes an increased concentration of dissolved elements in the water, especially nitrogen and phosphorus, which can result in excessive growth of algae and aquatic plants leading to eutrophication of the water body, i.e., depletion of dissolved oxygen. This detrimental effect on aquatic ecosystems compromises the availability of drinking water for human use. Groundwater is also experiencing significant changes in its chemical composition as a result of drought. The deeper water comes to the surface with a poorer chemical quality. Similarly, in coastal aquifers, the scarcity of freshwater recharge causes salinisation, which makes it unviable to maintain the crops that feed on these bodies of water.

Ecological impacts

Drought reduces plant growth and their capacity to sequester carbon, leading to forest decline and mortality and a shift in forests from being sinks to sources of CO₂ during drought episodes. This has adverse effects on ecosystem services. Thus, carbon fixation, regulation of the water cycle, maintenance of the diversity of fauna and flora, generation of wood products and landscape composition, all of which are ecosystem functions, are threatened by drought. This is compounded by the fact that dry natural areas are a worrying source of fuel for the forest fires, especially after wet years when a large amount of biomass accumulates. Drought also weakens trees and makes them more vulnerable to defoliating insects, increasing the damage directly associated with pests. It also negatively affects pastures on which the livestock sector feeds, which would add another economic problem resulting from the situation. Drought is also detrimental to wildlife. The consequent decrease in the reproductive potential of trees and increase in flammable fuels have negative impacts on herbivores and frugivores, which feed on seeds and fruits. Likewise, higher up the food chain, populations of carnivores and scavengers are also negatively affected.

Figure 1.8
Drought-stricken woodland in Spain



Indirect socio-economic impacts

Drought indirectly affects society and the economy. It can even lead to the disruption of local and global supply chains and production activities, resulting in temporary or permanent unemployment and loss of income. In addition, drought can lead to disease transmission due to poor water and air quality, food insecurity, malnutrition and, in extreme cases, widespread hunger and famine. This unfavourable context forces populations into internal or cross-border migration, increasing the risk of social conflict in the receiving region or country.

Beyond transmitted diseases, poor water quality leads to cardiovascular and respiratory problems, injuries, kidney disease, oesophageal cancer, mental health disorders and mortality. The most detrimental health effects of drought often fall disproportionately on children, the elderly, pregnant women, chronic patients, outdoor workers, the marginalised or impoverished. On the other hand, drought can have different effects on women and men; women are especially vulnerable in developing countries because they face discrimination: lower wages, limited educational opportunities and exclusion from political and decision-making processes.

The impacts of drought in Spain

Spain has traditionally been a country vulnerable to drought. There are numerous historical documents about its dramatic effects on society in each period. Due to the enormous dependence of the agricultural sector on the amount of rainfall, drought has caused famines, excess mortality and birth census. Visigothic records document that in 641 the drought was so severe that after seven years of rainfall deficit most of the olive groves in the Roman province of Baetica died. Another example is the droughts that affected the Ebro valley between 1641 and 1654, which caused a notable increase in cereal prices and a drop in the population.



The significant demographic effects of drought were also recorded in the 20th century. In fact, the last major drought-induced famine in Spain occurred in 1946, coinciding with Franco's period of economic autarchy, and resulted in several thousand deaths. With the developmentalism of the 1950s and 1960s, which transformed Spain from a fundamentally agrarian and rural country to a predominantly urban and industrial one, social and demographic vulnerability to drought diminished. Since then, although the impacts of subsequent droughts have been significant, they have been restricted to the economic and environmental spheres. In the last 75 years, no one has died of starvation due to drought in Spain. In recent decades, agricultural drought has become secondary and hydrological drought is currently the most relevant due to its role in urban supply, hydroelectricity production and agricultural irrigation, which has not ceased to grow in both extension and economic relevance.

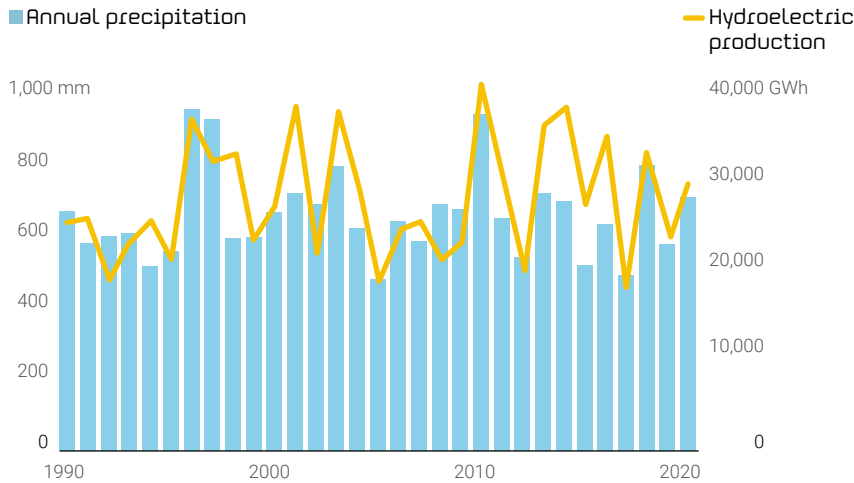
The drought in Catalunya has uncovered the old village flooded by the waters of the Sau reservoir, which was at 6.6% of its capacity in April 2023. / ISTOCK

In Spain, there is no direct record of the impacts caused by drought, so estimating them is complicated. However, the figures for some sectors are sufficiently representative of the enormous economic losses it causes, in addition to supply problems and significant social alarm. The droughts of 1980-1983 and 1991-1995 led to significant water supply problems in populated centres, especially in central and southern Spain.

Hydro-power production is also greatly affected by drought. For example, the brief but very intense drought in 2005 led to a significant drop in hydro-power production to 18,000 GWh (gigawatt hours) per year, which is the lowest figure since hydropower records began in 1965.

The sector most affected by drought in Spain is agriculture, especially irrigated agriculture, which is closely linked to hydrological drought conditions. Rainfed farming, although it suffers significant losses during dry years, has a much lower economic impact. For example, 2012 was the year in which agricultural insurance payments for dry arable crops were the highest, at 210 million euros. These figures, although large, are not comparable to the losses due to lack of water in irrigated areas, which can be estimated at several billion euros in a single region of Spain.

In addition to these direct impacts of the agricultural drought, there are other indirect impacts, which are difficult to quantify. A study on the direct and indirect economic effects of the 2005 drought in the Ebro valley estimated a decrease in agricultural production of 405 million euros. However, these losses were spread across different sectors, resulting in more than 300 million in indirect losses due to their effects on the agri-food industry or agricultural machinery. Furthermore, the drought caused the direct or indirect loss of more than 11,000 jobs.

Figure 1.9 Rainfall and hydro-power production

Evolution of precipitation and annual hydroelectric production in Spain between 1990 and 2020. / CSIC

Drought is responsible for half of the damage recorded in Spanish forests (defoliation, loss of biomass, decline), followed by biotic stress factors (insects, pathogens) - responsible for 24% of the damage - as shown by monitoring through regional, national or European forest health networks. Up to 80% of these affected forests recover within one to two years; the remainder may take longer. Finally, although Spain's forest biomass has increased considerably over the last sixty years, landscapes have become increasingly susceptible to the impacts of drought and wildfire.

14.

Living with drought: adaptations and solutions

Drought management

Given the enormous social and economic impacts of drought, different public administrations usually take measures to mitigate its effects. These measures are usually reactive, i.e., they are adopted when drought is already occurring, they are often ineffective, poorly coordinated and have little capacity to reduce vulnerability and risk. The fact that socio-economic activities are carried out without considering the risk of drought and that, when drought occurs, public administrations' mitigation provisions are subsidies, tax reductions or credits, which is the worst way to create a drought-resilient society.

In recent decades, the focus has been on the need for improved drought planning, readiness and recovery. In general, there are three fundamental pillars for adequate integrated drought risk management:

- Monitoring and early warning.
- Drought vulnerability and associated risk assessment.
- Mitigation, preparedness and response.

Indeed, to manage drought risk effectively, it is very important to understand the impacts, which ecosystems and societies are at risk and why. Moreover, effective integrated decision-making needs to be embedded in a series of iterative review cycles that involve improving strategies once a drought has occurred. Current estimates suggest that the benefit of taking proactive action in this regard is two to ten times greater than the cost of implementing reactive measures.

Figure 1.10 Pillars of Drought Management

Drought management experience in Spain

Spain's high vulnerability to drought has meant that its population has adapted to this anomaly in different ways throughout history. An example of this is the remains of numerous Roman dams and irrigated areas from the Arab period, which have survived up until the present day. Also since the 1950s, numerous actions have been taken to try to limit the country's vulnerability to drought.

Spain has been a pioneer in the development of adaptation measures for rainfed agriculture and extensive livestock farming. The most important of these was the implementation of an agricultural insurance policy in 1982, coordinated by the State Agricultural Insurance Entity, which has proved to be very useful and is still frequently taken out today. The main part of this insurance corresponds to rainfed crops, representing about 40% of the total. In addition, there is pasture insurance, using information provided by satellite images, which covers the extra supplies that farmers have to provide, such as feed, for livestock when the pasture does not grow sufficiently because of drought.



Almond orchard and flock of sheep. Spain has been a pioneer in establishing adaptation measures for rainfed agriculture and extensive livestock farming. / ISTOCK

In Spain, moreover, strategies have been developed to move from conventional agriculture, which is prone to water loss, to conservation agriculture, which is based on a drastic reduction (even elimination) of intensive tillage. This is done to maintain soil structure and favour the conservation of moisture and fertility. Conservation agriculture seeks to improve long-term crop productivity through the use of permanent ground cover, minimal soil disturbance and crop rotation. This technique can lead to 10% water savings in Spanish agriculture and avoids contamination of surface and groundwater.

In addition, along with crop rotation and diversification, another of the main measures developed is the choice of varieties adapted to water availability. This is possible due to breeding techniques to select or create new drought-resistant crops or by using traditional less productive varieties that had fallen into disuse, but which have better resistance and resilience traits. In recent years, the development of cutting-edge breeding techniques, based on advances in biotechnology, molecular biology and genome sequencing, has generated a gross economic added value of around one billion euros per year in Spain, and a strong reduction in water consumption thanks to the adaptation of varieties to water stress.



The development of plant breeding techniques in Spain has generated a gross economic added value of around 1 billion euros per year. / ISTOCK

Within the framework of sustainable intensive agriculture, significant improvements in irrigation systems have been implemented, both with more efficient hydraulic infrastructures and the implementation of innovative technologies, such as localised irrigation systems. These improvements aim to increase agricultural productivity with the least possible impact on the environment, as they minimise water losses and reduce the evaporation of water from the soil.

From an ecological point of view, adaptation measures have been implemented in Spain to reduce the vulnerability of ecosystems, especially in the case of forests, which occupy almost 30% of the national territory. Although very localised, measures to create less dense, structurally and functionally more diverse forests have been implemented to mitigate the negative impacts of droughts. Selective logging or even prescribed burning, which reduce density and basal area or contribute to creating more diverse and heterogeneous forests, help to reduce competition between trees for soil water. In addition, the use of cover thickets to help the regeneration of certain tree species is another adaptive management measure.

In Spain there are agroforestry systems, such as truffle oak plantations, where the use of drip irrigation is widespread. Irrigation is used because drought reduces the production and quality of the truffle.

In other systems, such as pastures, there are also viable adaptation alternatives: the selection of drought-resistant species or varieties, as in the case of some legumes, or the selection and application of edaphic microbiota that allow a more efficient use of water and nutrients. Finally, in transitional systems, such as riparian forests, which are particularly threatened throughout most of Europe by their conversion into urban and agricultural land, it is essential to maintain ecological flows and a seasonal regime, as the trees (poplar, ash) are very sensitive to low water levels and to a decrease in the water table in spring.

Since the main dimension of drought in Spain today is hydrological, the focus in recent decades has been on its management and adaptation when it occurs. This management began with the political regenerationism of the early 20th century, which was the basis for the development of a state policy for the planning and financing of hydraulic works. Since the 1950s, the hydrological regulation capacity in Spain has been considerably increased in order to increase availability and cushion deficits during dry years. However, this improvement in water regulation has gone hand in hand with an extraordinary increase in irrigated surface area.

Faced with the imperative of increasing the available water resources through regulation, the European Union's Water Framework Programme, adopted in 2000, has provided a new perspective for drought policy and management. Its directive indicated the need to complement river basin management plans with specific drought management programmes. Spain has been a pioneer in developing these river-basin plans, which have served as an indispensable tool for decision-making during hydrological droughts in the last decade.

These plans have contributed to limiting water restrictions in the water supply to population centres through better irrigation management. The drought-prevision plans are based on the availability of real-time information on the hydrological conditions of each basin, which are independent, and they are adapted to the specific characteristics of each basin; however the same



Spain is a pioneer in river-basin drought planning, which has contributed to limiting water supply restrictions in population centres through better management of irrigation systems



concept for drought monitoring is used in all cases. The plans include programmes of measures and an organisational framework for drought management in each sub-unit, with the involvement of key actors in each. In pre-alert and alert conditions, different priorities are established in the allocation of water uses, with water supply to the population always being a priority. The drought plans began to be implemented in 2007, they were revised in 2017 and in 2023, they were undergoing their second revision process.

In addition to drought plans, public administrations responsible for urban supply in population centres with more than 20,000 inhabitants must have drought contingency plans. These plans include different restrictions and measures to reduce water consumption and guarantee water supply according to different drought scenarios. Typically, urban plans include measures such as reducing irrigation frequencies, prohibiting the filling of swimming pools, alternation of water sources, etc. In addition, in Spain's main cities, actions have been implemented to reduce water consumption, in some cases by increasing the price per cubic metre of water, but also by running awareness campaigns on responsible consumption, installing individual meters, promoting water-saving technologies or controlling illegal connections to the supply network. As a result, since the beginning of the 21st century, there has been a progressive and continuous reduction in per capita water consumption, from over 160 m³/year in 2000 to less than 120 m³/year nowadays.



Finally, it should be pointed out that, despite the changes brought about by the Water Framework Directive and the drought plans in Spain, drought management remains largely reactive at present. Thus they take the form of legislation and credits by the governments to subsidise losses in the affected sectors, mainly the agricultural sector. Moreover, these measures are often accompanied by plans for more water-regulating infrastructures or even water transfers between river-basins. So, on the one hand, Spain has joined the pioneering Water Framework Directive increasing water regulation and implementing other measures (such as the modernisation of irrigation systems, the construction of desalination plants and even the reuse of waste water). On the other hand, paradoxically, demand is still considerably high at present, due to the enormous increase in irrigated areas and the intensification of irrigation. It is this factor that prevents demands from being met during drought events and explains why the Spanish hydrological system and irrigated agriculture are currently so vulnerable to drought.

two



The CSIC's Contribution to Studying and Adapting to Drought

FOR decades, various CSIC institutes have been working on different lines of research directly or indirectly related to drought. This effort has led to considerable progress in the multidisciplinary understanding of drought, with a view to adopting the necessary measures to mitigate its effects and to adapt.



CSIC researchers perform drought simulation experiments. / INIA

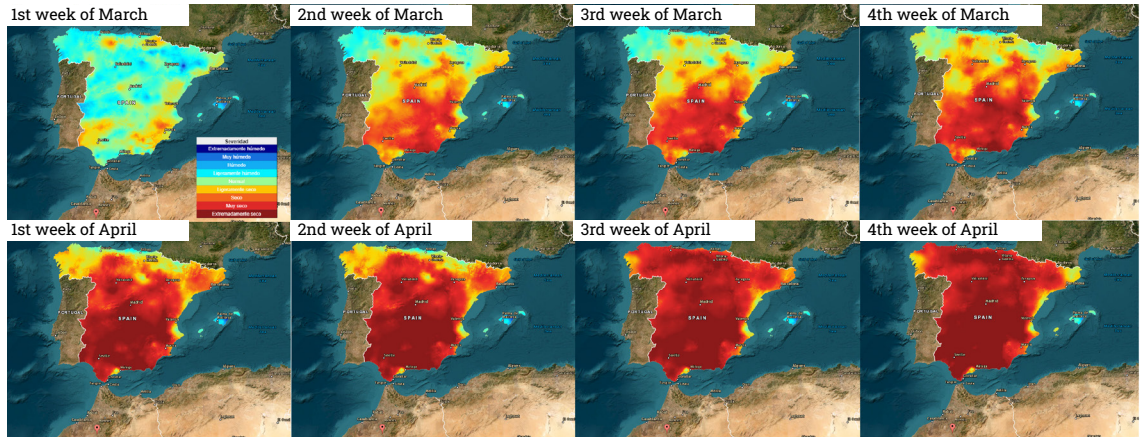
2.1.

Drought from a climate perspective

THE sheer complexity of drought has required intensive research to develop tools to help us to quantify it objectively and to compare its severity in regions with different hydro-climatic characteristics. At the CSIC, researchers have focused their work in this way to develop indices to quantify meteorological drought. In particular, the *Standardized Precipitation Evapotranspiration Index* has made it possible to include the effect of atmospheric evaporative demand in the quantification of drought. This indicator has now become a benchmark for quantifying dry periods and is used in scientific studies by researchers around the world and by national meteorological services for the development of risk monitoring and early warning systems. Along with this widely used indicator, the *Standardised Evapotranspiration Deficit Index* has been developed, with great potential for diagnosing agricultural and ecological droughts as it is based on the evapotranspiration deficit, which is the difference between the water that plants actually transpire and that demanded by the atmosphere, making it an excellent indicator of canopy water stress.

In addition to the development of indicators, methodologies have been developed to estimate more accurately the hazard of climatic droughts of different intensity, allowing the creation of probability mappings for better risk assessment. Methods have also been developed for better quantification of flash droughts, mainly associated with heatwaves.

One of the fundamental pillars for the implementation of efficient drought management plans is the availability of real time information on the severity, extent and type of drought. Since the predictions of conditions present significant uncertainties, knowing to what extent drought affects different regions with greater or lesser severity and how it is evolving, both in terms of its spatial distribution and its intensity, allows for improved risk management. The CSIC was a pioneer in the development of global drought monitoring systems, with the launch of a global drought monitor in 2012 based on the *Standardized Precipitation Evapotranspiration Index* (SPEI). This monitor provides up-to-date information on the drought severity worldwide. Given its



Progression of the 2023 drought in Spain based on the meteorological drought monitor and the SPEI at a three-month time scale. / csic

usefulness, it has been implemented by international organisations and companies during drought episodes. In addition, CSIC researchers have also recently developed a more advanced monitor, which is updated with a higher time frequency and has a higher spatial resolution and physical consistency, which helps to determine drought conditions in regions where different crops are dominant.

At the national level, researchers have recently developed a meteorological drought monitoring system that makes it possible to determine with a weekly time frequency and at a spatial resolution of one kilometre. This system has been transferred to the Spanish State Meteorological Agency to monitor meteorological drought in Spain.

Although the seasonal prediction of droughts based on climate modelling is a very complex aspect, the CSIC has performed research along these lines with the aim of improving the prediction of droughts corresponding to specific atmospheric situations. The improvement of statistical procedures is applied to seasonal prediction models to improve their confidence and the determination of the connection between snow cover in the northern hemisphere and its impact on the prediction of precipitation in Europe during the winter.

This analysis aims to improve seasonal forecasting of future droughts in order to strengthen preparedness and risk management.

Given the high uncertainty in drought prediction, it is necessary to advance our knowledge of the underlying physical mechanisms. Finding out what connections exist between atmospheric dynamics and their origin is a necessary prior step to developing more effective predictive models. For more than a decade CSIC researchers have been studying the dynamic and thermodynamic mechanisms of droughts at different spatial scales, from global to regional.

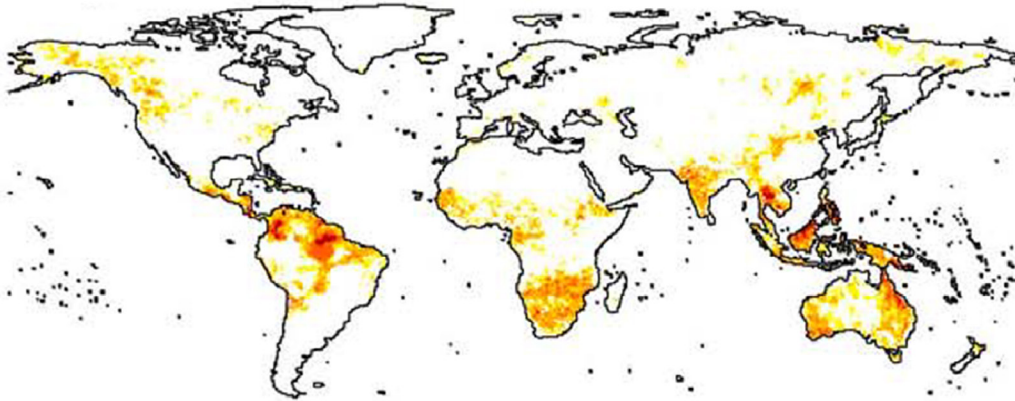
On a global scale, the uneven effect that mechanisms such as the El Niño-South Pacific Oscillation have on the occurrence of droughts in different regions of the globe was discovered.

Researchers identified how the effects of this oscillation propagate to different regions spatially and temporally, making more reliable drought prediction possible in those regions a few months in advance.

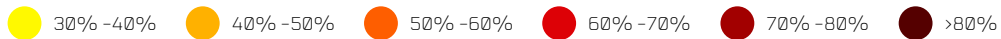
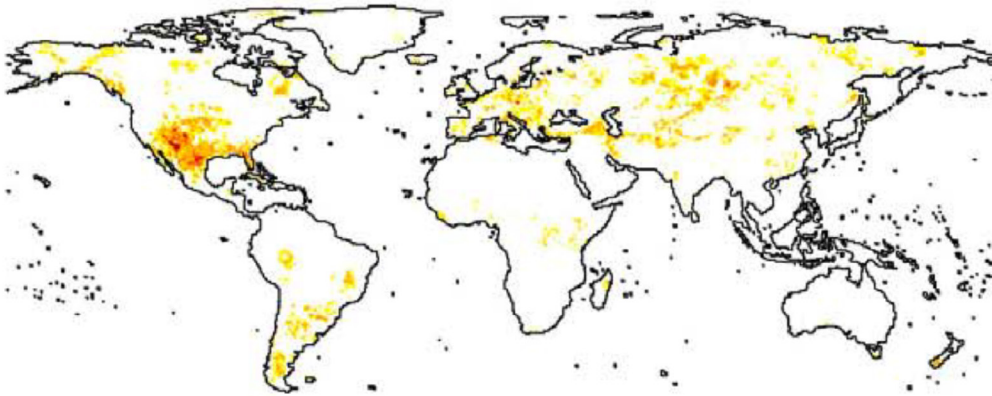
The development of new methodologies at the CSIC for the characterisation of blocking anticyclones and atmospheric stagnation has opened up the possibility of gaining a better understanding of the origin of droughts. In addition to the studies focused on specific episodes, lessons can be drawn about the current difficulties in predicting these phenomena and indicates where to focus efforts with a view to medium- term prediction.

Furthermore, knowing how drought has behaved over time and space is essential to determine to what extent the phenomenon is changing and whether these changes can be attributed to the current process of climate change. The CSIC carries out geological studies through lake sediment analyses to study large climatic fluctuations on a large temporal scale, indicative of predominantly dry periods. These studies allow us to see the evolution of drought in a larger context and to provide a more reliable picture of the exceptional nature of droughts currently being experienced as a result of anthropogenic forcing caused by greenhouse gas emissions.

EL NIÑO



LA NIÑA



Likelihood of droughts
occurring in the world
associated with El Niño
and La Niña. / csc

On a documentary and instrumental scale, the CSIC has carried out regional research into the reconstruction of droughts based on documentary sources from the last four centuries; on a global scale, researchers have also studied the spatial-temporal dynamics of meteorological drought. They have found that drought is essentially stationary due to the dynamics of rainfall, its high temporal variability and the intensification of drought episodes due to global warming. Studies in Spain have shown that these episodes are highly variable spatially and few have affected the country as a whole. The contributions of this line of research provide a better understanding of the behaviour of drought, an essential aspect for making progress in drought prediction and adaptation.

The prediction of future drought conditions according to climate change scenarios is essential for long-term risk management. The CSIC has worked on the analysis of future projections of this phenomenon and the determination of its uncertainties, developing key methodological aspects that allow its interpretation in scenarios of high greenhouse gas emissions, and focusing on how the physiological mechanisms of plants will respond and be interpreted in the models.

The CSIC has also been conducting research for more than ten years to improve the processing of climate change models and their spatial detail at regional scales, and to reduce their uncertainty. The result of this research has been two tools that provide very efficient access to climate model data at both national and international scales. These make it easier for managers in public administrations and businesses to access the most up-to-date and reliable data on future drought projections in order to improve long-term adaptation plans.

22.

Plant adaptation to drought and water use in agriculture

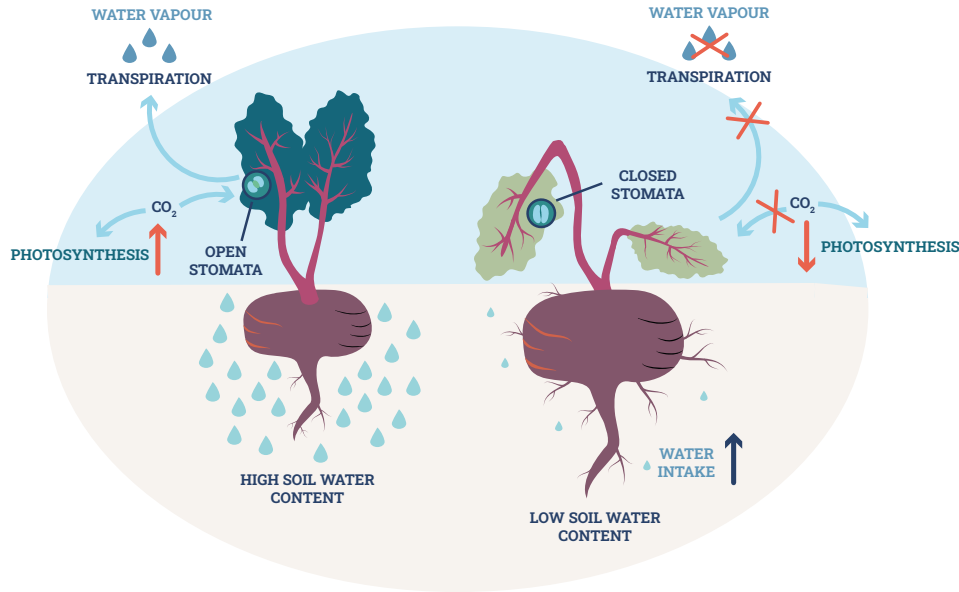
IN view of the need to produce more food for a growing population, increasing at unprecedented rates but with increasingly limited natural resources, the CSIC is developing lines of research with studies focusing on plants, water and soil to increase water productivity. Although the protagonist in agricultural systems is the crop, water and soil are key elements for plant growth and higher yields, and thus for plant-based food production.

The CSIC is making great efforts to understand the responses that plants develop at the physiological and molecular level when they are subjected to drought stress conditions, as well as the traits of each species or variety that define their different responses. This information facilitates the development of soil and plant indicators and allows the application of more precise and efficient irrigation strategies, with the aim of improving the efficiency of water use in crops.

One of the first responses of plants to drought is the closure of stomata to prevent water loss through transpiration, which has a negative impact on photosynthesis and thus on plant growth and development. At the root level, plants quickly activate mechanisms to stimulate water uptake from the soil, such as changes in root growth towards deeper areas where water is more abundant. Therefore, the CSIC is studying stomatal regulation, water transport and root development as key strategies to reduce water use in agriculture and improve resistance to drought stress in crop plants.

Drought also affects plant nutrition by altering nutrient uptake and transport, which negatively affects water uptake and transpiration. At CSIC, several research groups are working to identify the molecular and physiological mechanisms that regulate the uptake and transport of ions such as potassium and chloride in plants, and how their agronomic application can improve drought symptoms in crops.

Figure 2.1 Plant physiological responses to drought



IRENE CUESTA (CSIC)

The identification of physiological response mechanisms to drought facilitates the selection of varieties that are more resistant and tolerant to water stress. This information is also very useful for the study of genes involved in the response to water stress through genetic improvement. In particular, work is being done on the identification and characterisation of drought resistance genes and traits in wild relatives of the crop. These genes will be transferred to important agricultural varieties, with the aim of increasing water productivity, breeding new cultivars and achieving better crop yield, tolerance and resilience to drought. Another novel and related line of research focuses on the evaluation of polyploidy (more than two chromosome copies) as a positive trait for plant tolerance to drought.

The CSIC is also applying biomedical techniques to agricultural biotechnology, such as the use of pharmaceuticals and biostimulants to modify plant hormone signalling responses (abscisic acid or brassinosteroids) and other physiological responses that can improve plant resistance to drought.

In addition, the CSIC is working to ensure that the knowledge acquired is transferred to the agricultural sector and society in general, which is particularly important in the current context of drought. In general, innovations have not been widely adapted by the sector; thus the aim is to bridge the gap with bottom-up, interdisciplinary approaches in an open environment that makes intensive use of emerging technologies to improve the sustainability of irrigated agriculture. In addition, some of the projects include cost-benefit analyses to quantify the economic benefits of using irrigation scheduling models, in order to encourage users to adopt these systems.

On the other hand, knowledge of crop responses to soil water deficit helps researchers develop scientific and technological solutions to the problem of drought in the agricultural sector. In particular, it facilitates the application and development of innovative technological approaches that allow the sector to progress in the field of digitalisation and the sustainable use of irrigation; this is also a field of research being performed by different CSIC groups. Irrigated agriculture is central to food production, occupying only 17% of the world's cultivated area but producing 40% of food. However, with less and less water available to meet crop demands, there is a need to increase water productivity. In this respect, in addition to contributing to the modernisation of irrigation systems, CSIC is advancing in the use of proximal and remote sensors to help farmers increase productivity without increasing the amount of irrigation in a context of intensive and digital agriculture. Indeed, proximal sensors are being developed and used in soil, but especially in plants, as they register the water status of the soil and the atmosphere, as well as the plant's response to environmental conditions.



The extensive development of sensors (sap flow, stem diameter variation, leaf turgor pressure, etc.) and data transmission systems facilitates real-time access to data, thus making it easier to monitor water stress and manage irrigation more efficiently. Thus, the ultimate goal is to develop systems that intelligently decide when and how much to irrigate thanks to the precise determination of the crop's water status, to which environmental variables or the phenological period can be added. In addition, there are projects in which these systems are being developed for crops grown without soil or with different water qualities. In fact, different CSIC research teams working on the use of non-conventional water for irrigation. In this way, they aim to improve the possibilities of adapting to drought by reducing the pressure on water resources, as clean water is replaced by non-conventional water.



At the CSIC, the genes involved in the physiological response to water stress are being studied through genetic improvement. / csic



In the context of digital and smart agriculture, tools are also being developed to determine the water status of crops with remote sensors (thermal images, multi- and hyperspectral cameras, fluorometers, etc.) and the use of satellites and drones. In this sense, the CSIC is developing indicators derived from thermal, multi- and hyperspectral information for monitoring water status and irrigation scheduling. These same techniques are also being developed for the quantification of soil evaporation and crop transpiration to incorporate the spatial component by remote sensing to irrigation scheduling models over large areas. The estimation of evapotranspiration is a very complex aspect, but it is critical for the proper determination of irrigation demands and the optimisation of available water reserves, which are strongly affected by dry periods. Research is also carried out to develop and implement these and other new innovative digital technologies and procedures to improve irrigation efficiency, using simple low-cost solutions (low-cost hardware simplified data-driven models, open-source software integrated in user-friendly platforms, etc.), in order to facilitate their use by small-scale farmers.

Using this knowledge and databases produced by sensors, both in-field and remote, advanced agronomic models are being developed at CSIC to determine crop evapotranspiration and integrate them into decision support systems for more efficient irrigation scheduling based on crop type, climate and the quantity and quality of water available for this purpose. Ideally, these models should be explicitly based on the physiological mechanisms underlying the response of plants to soil water deficit so that they provide an integrated understanding of the results from the sensors. Thus they can be extrapolated to different spatial and temporal scales from which they have been calibrated, which is why some CSIC groups are working in this direction. This characteristic differentiates them from those developed by artificial intelligence, which are also used for database management. The advances provided by the so-called *Internet of Things* are also being used in decision support systems.



Measures taken on water management are closely related to soil, as the two are intimately linked. Therefore, part of the research being done in the agricultural field in relation to drought focuses on promoting sustainable agricultural practices that favour the soil's capacity to retain water, so as to reduce the impact of drought; this would be the case of reducing the application of inputs such as irrigation. The CSIC, through various projects, is assessing the impact of crop diversification on water use efficiency. Different sustainable agricultural practices are also being assessed to control drought-related problems such as erosion. In recent years, the impact of agro-ecosystem management practices on the services they provide has also been investigated. Some of the most innovative approaches to increase water retention in the soil are those that aim to improve the physical and chemical properties and structure of the soil by managing mineral and organic nutrients from the processing of agricultural or urban wastes, and with the help of different technologies. In addition, efforts are being made to identify micro-organisms with plant growth-promoting activities, useful for improving the productivity of cultivated species. Researchers are also investigating the effect of the microbial community in agro-ecosystem soils irrigated with desalinated water and their interaction with organic changes. The use of endophytic and epiphytic micro-organisms as probiotic agents in plants represents an alternative to the use of agrochemicals and a step forward in plant breeding, thus contributing to more sustainable agriculture.

2.3.

Drought from a hydrological perspective

STUDIES addressing hydrological drought is one of the main research lines underway at the CSIC, with studies ranging from the monitoring of gauged basins in mountainous areas to others of a drought from a hydrological perspective continental nature. In the light of these studies, researchers have confirmed the importance of vegetation cover in surface runoff production and annual flow recession curves. Thanks to the field experiments carried out for more than twenty years by a multi-disciplinary team at the CSIC, it has been possible to verify how widespread re-vegetation processes in the Mediterranean mountains are fundamental to explaining the recent evolution of flow rates and the intensification of hydrological droughts. Studies at larger spatial scales have shown how hydrological droughts respond very differently to meteorological drought conditions depending on the system being analysed, with faster responses in mountain headwater areas and slower responses in the middle courses of large rivers and in reservoir systems.

In some hydrological systems, hydrological management has been shown to be a major factor in generating downstream drought conditions. In addition, the researchers have documented how hydrological droughts are worsening in Spain, mainly as a result of water demands from irrigation. They have also determined that spatial variations in hydrological droughts at the European level are mainly due to changes in water use rather than to climate change processes.

From the perspective of groundwater, the CSIC is conducting research along different lines to improve knowledge of Spanish aquifers. It is committed to the mathematical modelling of these aquifers to better understand their hydrodynamics and to assess the impact of climate change on renewable groundwater resources. Some of the studies on which work is currently being carried out pay particular attention to the possible effects on groundwater-dependent ecosystems, in particular wetlands,



such as Doñana or the Mar Menor. They also investigate the relationship between intensive exploitation, the lowering of piezometric levels and land surface subsidence. Other studies address changes in groundwater quality in coastal aquifers due to marine intrusion and the delimitation of hydrogeological divides in water-bodies shared between different hydrographic districts. Finally studies are underway on river-aquifer relations and ancestral techniques (such as recharge ditches or *careos*) for managing surface and groundwater as a tool for overcoming the effects of climate change; and the improvement of urban supplies in the small sparsely populated towns in Spain.

Researchers have documented how hydrological droughts are worsening in Spain due to irrigation demands. / iStock

The CSIC also conducts research into managing aquifer recharge with reclaimed water, the reuse of water with eco-efficient systems, the study of complex karst systems, the salinisation of water and its impact on ecosystems, the analysis of lakes in the context of global change, the contamination of groundwater in contexts of scarcity and the study of aquatic macroinvertebrates, as indicators of climate change in rivers.

In terms of impacts on biogeochemical cycles, CSIC centres carry out cutting-edge science on pollution-related impacts on hydrogeochemical systems such as aquifers. CSIC teams are working on the analysis of water pollutants in river courses to determine the implications for water recycling and its use for urban supply or agricultural purposes. In this sense, the effects of droughts on the geochemistry and biochemistry of river courses have been analysed, affecting the content of dissolved organic matter, nutrient cycling, pollutant concentration, and have consequences on river ecosystems and their transport along river basins.

CSIC studies show a high correlation between hydrological drought conditions and water temperature values, which demonstrates the need to maintain adequate flow levels in order to control processes that alter water quality.

Furthermore, CSIC researchers are currently working to develop eco-efficient systems to treat and reuse wastewater in the Mediterranean region. It has been proven that, during low water levels, there is a reduction in the nutrient supply from terrestrial ecosystems and also lack of oxygen and eutrophication, which significantly affects the health of water bodies.

2.4.

Drought from an ecological and environmental perspective

SPANISH research on drought in the fields of global change ecology and forest sciences is of high quality and quantity. The contribution of CSIC research groups has been fundamental. For example, long-term rainfall exclusion experiments have shown how drought events reduce the growth, productivity and reproductive capacity of different tree and shrub species. The extent to which some Mediterranean plant species acclimatise and are able to tolerate severe or long droughts by modifying their growth or carbon sequestration rates has also been measured. In addition, it has been observed that drought can interact with soil pathogens and reduce their impacts on trees, as some of them require a certain amount of soil moisture.

These prospective and experimental studies have been complemented with retrospective and observational studies based on dendrochronological data (growth rings) and regional forest damage networks. In this way, it has been possible to link episodes of forest decline and mortality with droughts and, thus, to quantify the growth and productivity recovery period in Spain, and even on a global scale.

Furthermore, the response of vegetation to droughts in terms of its photosynthetic activity has been tested at both regional and global levels using satellite imagery. Results show ecosystems respond differently to dry spells and determine how increased atmospheric evaporative demand increases ecosystem stress and may lead to degradation processes in overexploited areas.

Other observational research lines have focused on the impacts of droughts on soil functioning and productivity in iconic Iberian ecosystems such as dehesas. Their studies have shown that water deficit reduces the microbial biomass of the soil, which impairs nutrient uptake by tree roots.



At the ecosystem level, CSIC groups have observed negative impacts of drought on the productivity and phenology of plant communities in National Parks such as Doñana using remote sensing combined with gas flux towers.

Other CSIC studies have evaluated the responses of plant communities to drought in semi-arid regions of southeastern and northeastern Spain, detecting changes in the interactions between plant species, in the chemical composition of their tissues and in how they take up water and nutrients from the soil. On the other hand, researchers have found that in Mediterranean climate zones, drought is often linked to torrential rains, which cause erosion and loss of soils and vegetation. At the global level, CSIC studies have shown that drought can interact with other components of global change and increase the stress on soil ecosystems, reducing their services.

Drought also affects the chemical composition of plants, as demonstrated by CSIC researchers. This impacts on animal consumers and their diets and modifies food webs. For example, monitoring programmes carried out in Doñana found historical reductions in bird populations linked to severe droughts, such as the one Spain experienced in 2022.

The CSIC is analysing the effects of droughts on the increase in the number and severity of wildfires. Researchers have found that the vulnerability of forests to exposure to drought-related wildfires has increased significantly. This is mainly a result of rural abandonment and the increase in natural vegetation, which has led to dry periods being one of the main drivers of wildfires. The impacts of droughts and fires on forest species are also under study, with emphasis on forest decline and the use of prescribed burning to mitigate the negative impacts of water scarcity on trees.



Drought-related wildfires
have increased mainly
due to rural abandonment
and forest expansion and
encroachment



Management plays a fundamental role in the adaptation of forests to drought. The CSIC is leading research on the capacity of certain silvicultural practices, such as thinning (the appropriate management of stand density), to improve the adaptation of forests to drought. In particular, research teams have found that thinning increases tree resistance to drought, maximises growth during dry spells, and accelerates post-drought forest recovery rates (i.e., improves resilience). The current line of research is focused on better understanding the physiological mechanisms that explain this improved adaptation and on determining the optimal densities for different species and climates.

The CSIC has studied in depth the sensitivity of soil respiration to drought, an aspect that has important implications for the net carbon balance. Field-studies have been carried out using experimental plots, and have shown the important role of soil moisture in CO₂ fluxes and summer storms in variations of these the dominant role of explaining the inter-annual fluxes. Studies have concluded that soil degradation interacts with soil moisture in the studied regions, with important implications for the carbon balance of these ecosystems.



Another CSIC research team is working on the exchange of CO₂ fluxes between the land surface and the atmosphere in semi-arid ecosystems, in particular addressing the role of biological and non-biological processes. This work shows that these ecosystems become net emitters of CO₂ during dry episodes. In this regard, another CSIC institute has found that soil respiration and atmospheric CO₂ exchanges are more greatly affected by droughts than by the amount of nutrients present in the soil. In addition, they also found that the effects of this temperature anomaly on soil respiration can be prolonged once the drought is over, due to changes in the soil microbial communities.

Other research groups have compared the CO₂ fluxes between degraded semi-arid and well-conserved vegetation areas, showing that degraded areas are high CO₂ emitters, while well-conserved areas sequester carbon on a net basis. These results have broad implications for the management and conservation of semi-arid ecosystems.

2.5.

Drought from a socio- economic perspective

GIVEN its complexity, there are no reliable estimates or statistics on the direct and indirect impacts caused by droughts. This constraint greatly limits the ability to estimate vulnerability to drought and the related risks. A multidisciplinary team from the CSIC has tested the capacity of different climate drought indices to identify their effect on rainfed crop production and on forestry activity and production. This research has made it possible to identify the most useful indicators for each territory and each sector, which are clearly useful for the development of more effective drought monitoring and early warning systems. Furthermore, some researchers are currently using artificial intelligence technologies to estimate the social and economic impact of droughts, based on the huge volumes of documentary information available in a variety of archives, including newspaper archives.

The CSIC also studies droughts from the point of view of their institutional management. Specifically, research has addressed social behaviour with respect to water resource management measures to tackle drought. The results have shown that the general acceptance of maintaining a water policy based on the construction of public works has decreased in recent years. However, there is considerable resistance from the agricultural sector to adopt a paradigm shift towards solutions focused on managing demand. Understanding the social perception of different water governance models and their alternatives is of great importance if we are to improve drought management from an institutional perspective.

three



Conclusions and Recommendations

Conclusions



Drought poses **the most complex hydro-climatic risk** as it is difficult to quantify its severity, surface extension and impacts. This is due to the fact that there are different drought types, which propagate differently overtime, space and in different natural and socio-economic systems, incurring innumerable indirect impacts. All this makes both studying drought and establishing appropriate adaptation and risk mitigation measures highly complex.



Drought **affects all regions of the world**, regardless of whether their climate is dry or wet. It is characterised by **high temporal variability** and the impossibility of predicting it. In recent decades we have witnessed an increase in the severity of dry periods, not as a consequence of changes in rainfall, which are not very significant, but due to the increase in atmospheric evaporative demand, which has risen sharply due to global warming. Moreover, excess demand from some sectors is significantly increasing the severity of hydrological droughts. In the future, due to climate change processes, the severity and frequency of drought is expected to rise significantly.



Drought **negatively impacts many systems, ranging from agricultural and livestock to ecological**, causing dramatic economic losses, but also reducing the provision of ecosystem services. Drought has a negative impact on productivity and on the yield and quality of crops and forests due to loss of cell turgor, reduced assimilation of CO₂ and growth rates, increased oxidative stress and nutritional imbalance. This leads to a decrease in the production and quality of food, timber and non-timber forest products (fruit, cork, truffle), higher prices and loss of income for farmers and the forestry sector.



Drought directly affects livestock by reducing the availability of pasture and compromising the production of key crops for livestock feed. It also impacts on the practice of transhumance, making seasonal livestock movements difficult and contributing to soil degradation. This has important economic and nutritional implications for the livestock industry.



Drought compromises the CO₂ sequestration capacity of forests and their climate change mitigation potential, leading to forest decline and tree mortality. It may transform some forests from carbon sinks to sources. Furthermore, it makes forest ecosystems more vulnerable to other disturbances, such as wildfires. Drought reduces their biomass and biodiversity, altering food webs and often converting them into communities that are more tolerant to water deficit, such as shrubs or holm oak forests, to the detriment of conifers.



The fight against drought **requires an integrated vision of water in river basins**, as well as a **more detailed and continuously updated knowledge applied to its management**, which allows understanding its dynamics and the characteristics of all the phases of the local water cycle, with special emphasis on the strategic role that groundwater and the joint use of groundwater and surface water can play in overcoming temporary and structural dry episodes.



In many CSIC institutes, **research on drought** is being carried out **in a wide range of disciplines** ranging from climatology to agronomy, hydrology, ecology and forest sciences, etc. This research is making decisive contributions, with highly notable scientific and socio-economic impacts, deepening our understanding of the phenomenon and advancing in the search for efficient solutions that will allow us to better adapt to the risk of drought and to mitigate its impacts.

Recommendations



Measures aimed at reducing the risk of drought can be highly diverse and address very different sectors. From Spain's extensive experience, characterised by both success and failure in drought adaptation, recommendations can be drawn, to be implemented inside and outside our country. These should be useful to mitigate the effects of all types of drought (agricultural, ecological, hydrological and socio-economic) and, in the case of water resources, to encourage both increased water availability and the control of demand. For example, actions can be taken that increase runoff generation and water infiltration in the headwater areas through more efficient forest management. This would prevent the growth of forests in mountain areas from compromising water availability downstream.



Actions to **reduce exposure to drought** can be very diverse, and include reducing water demands, growing species and varieties better adapted to water scarcity conditions, optimising water use through sustainable fertigation strategies, diversifying livestock feed sources, improving management of irrigated areas, etc.



Reducing the vulnerability of societies and ecosystems can also be achieved through better conservation and management of grazing land and forests; water storage measures; water infrastructure; conservation agriculture or the addition of organic matter to improve water retention capacity of the soil and favour the circular economy, which would maximise the sequestration of organic matter (carbon) in the soil; the development of drought management plans adapted to the water resources of each region, etc.



At the local level, the measures could be taken to address the water bodies. The solutions involve **optimising the management of reservoirs and groundwater, as well as water infrastructures**, by improving supply and irrigation systems to limit water losses or by recycling water.



The case of **groundwater** can be considered special because, although drought negatively affects the recharge of aquifers, their volume normally takes a long time to respond, so it takes a long time for them to be affected. For this reason, in many places groundwater can be used intensively on an ad hoc basis to alleviate drought deficits. These periods of intensive use need to be followed by rest periods when recharge is more abundant so that the volumes extracted from aquifers are recovered. Such strategies should be adopted, taking into account the environmental flows necessary for the maintenance of natural discharges (land and submarine springs). In this respect, the joint use of surface water and groundwater is, often, the most robust drought adaptation tool from the perspective of sustainable water resource management. Contamination of these aquifers must therefore be avoided in the long term.



Manifold **measures can be taken in the agricultural sector at the local level**. These include the selection of species and varieties that are resistant to water deficits or show increased water use efficiency, obtained through the selection of resistance genes or traits in comprehensive breeding programmes. Major advances in water use efficiency can be achieved by increasing crop-water productivity, i.e., the yield produced, be it grain, biomass or another variable, per unit of water consumed.

Reducing water consumption in agriculture by improving or implementing more efficient irrigation systems and strategies is another major option proposed to reduce water consumption in agriculture, without severely penalizing the yield. This can be achieved through developing novel and inexpensive devices that can efficiently monitor the water status of cultivated plants. The use of mechanistic models that are integrated into irrigation decision support systems can be very useful to interpret the results of these devices and optimise irrigation. Moreover, it is important to improve soil erosion control and integrated soil fertility management through crop rotation, or less intensive tillage. This would maintain vegetation cover on crops for as long as possible (especially during the drier seasons) through the application of organic matter coming from the circular economy. This would favour the water retention and organic matter storage, which in turn would reduce fertilisation and irrigation requirements.



Regarding livestock activities, measures may include **improvements of access to water sources by livestock, the seasonal rotation of grazing and mobility, and even grazing land management** using different animal species or adequate grazing pressure to prevent overexploitation and erosion processes. In the case of forested areas, forest management can be optimised to avoid excessive tree density leading to high competition with other species. for available resources and increasing the vulnerability of these ecosystems to decline and mortality during drought episodes. Optimisation can also include reforestation with drought resistant or tolerant species or varieties, adapted to the environment. Forest management should aim to create structurally and functionally more diverse landscapes that are more resilient to drought and other disturbances. We should become accustomed to more open forests, often coexisting with less productive scrub or grassland, which accumulate less fuel and are more water efficient.



On a river basin scale, it is necessary to **generate river basin drought plans that increase the efficiency of water resource management** when dry periods occur. This may include monitoring and early warning systems that are optimal and adapted to regional characteristics, and alert thresholds and actions established a priori with the aim of making available resources more efficient and avoiding water restrictions, as far as possible. Monitoring systems can be integrated with impact-measurement systems, e.g., forest health networks, which assess tree defoliation and can be complemented by remote sensing data.



At the national level, **drought monitoring systems** can be established to **help more effective decision making** during dry spells, hydrological regulation measures, agricultural incentive measures such as subsidies and grants to modernise irrigation and improve its efficiency. Also the development of advisory programmes for farmers that can then be implemented at regional and local levels. Setting up and managing an agricultural insurance system is also a measure that should be managed nationally and which, as shown in Spain, has been extremely successful in reducing the impacts of drought on agriculture. Finally, intervention in the markets to address economic or financial problems arising from drought could also be a potential action to be taken at the state level.



At the level of multinational organisations, such as the European Union, **measures** can be considered **for cooperation in water resources management**, highly necessary necessary in transboundary basins; **the development of common legislation and directives** to improve drought, as in the case of the Water Framework Directive; or **price controls for agricultural products or inputs needed by farms**, e.g., at the energy level. At the multilateral and global level, it is possible to negotiate regional compensation mechanisms, the implementation of subsidies or the creation of a roadmap with recommendations for mitigating the impacts of drought, developed by the relevant international agencies.



Finally, it should be noted that, for proactive drought management measures to be successful, it is necessary to involve the **key actors at the local and regional levels**, as they know the characteristics and problems existing at the specific level. These stakeholders should include farmers' associations, river basin management bodies, regional governments, financial sector stakeholders, environmental associations, irrigation communities, farmers and forest owners, municipalities, etc. Coordination between all of them is of great importance, as it is essential to consider the different interests of each sector, which are often divergent. Thus consensual measures can be agreed upon to efficiently address the issues related to drought, with a view to creating drought-resilient ecosystems and societies.



four



List of Centres

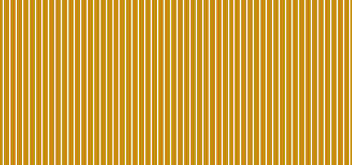


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