# CLIMATE CRISIS: Droughts

## EO R&D activities for water resources management

know.space

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**know.** */nəʊ/v.*

to understand clearly and with certainty

## About us

**know.**space[1] is a specialist space economics and strategy consultancy, with offices in London, and Edinburgh. It is motivated by a single mission: to be the source of **authoritative economic knowledge for the space sector**.

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## Acknowledgements

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**Cover image:** European Union, Copernicus Sentinel-3 imagery


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# Climate Change contributes to droughts …

The *Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report* highlights that **anthropogenic climate change** – the long-term shifts in temperatures and weather patterns caused by human activities – leads to **increasing, concurrent, and more potent extreme environmental phenomena**[i].

**Climate change contributes to droughts by disrupting the water cycle**[ii]. Increasing global temperatures accelerate the rate of evapotranspiration, which can lead to a shift of rain belts and deserts. These changing land-atmosphere feedback loops can result in local anomalies which can amplify larger-scale anomalies (e.g. driven by El Niño-Southern Oscillation). These are then **exacerbated by inadequate water management and usage**, resulting in droughts.

This is problematic, as **humans heavily depend on water**[iii]. Droughts are **significantly destructive**, impacting homes, farmland, human and animal lives, food and fuel supplies etc[iv]. More specifically, droughts **directly impact the supply chain of numerous sectors** beyond *just* agriculture, for example leading to negative impacts on energy production, inland water transportation, drinking water supply, and infrastructure (e.g. land subsidence).

Droughts can also lead to **wide-ranging domino effects**, and thus result in considerable damages socially (e.g. safety and well-being of the population), economically (e.g. loss of crops and destruction of infrastructure), and environmentally (e.g. disrupted ecosystems leading to domino effects)[v]. For example, with 3°C global warming in 2100 and assuming no adaptation, absolute annual drought losses for the EU and UK **could be 5 times higher compared to present** (an increase from €9 billion to €45 billion per year).[vi] An additional degree of warming would bring losses to €65 billion per year[vii].

Additionally, **droughts heavily influence compound events**, such as heatwaves and wildfires, further amplifying damages and costs[viii].

> *"Drought plays a substantial role in the occurrence of the compound and cascading events of dry hazards, especially in southern Europe as it drives duration of cascading events. Moreover, drought is the most frequent hazard-precursor in cascading events."*[ix]

# … notably in France in 2022

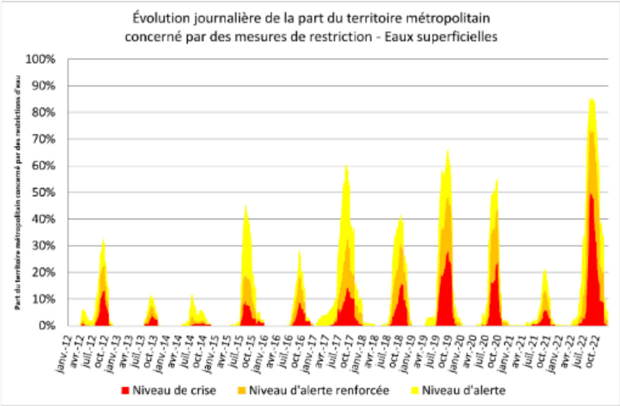
Many European countries have been facing extreme and repeated heatwaves and droughts[x]. **France has been particularly affected** over the past decade, especially in **2022**, **which was the hottest and second driest year on record**[xi]. This impacted all departments of metropolitan France[xii].

The **2022 drought was the second longest** in French history and was particularly severe in the spring and summer period (60% rainfall deficit in May, 85% in July)[xiii]. On top of these extended drought conditions, France faced 3 consecutive climate change-induced heatwaves (33 heatwave days in total – a record), major forest fires, an ocean heat wave in the Mediterranean sea, intense hail storms, and windy and tornadic conditions[xiv].

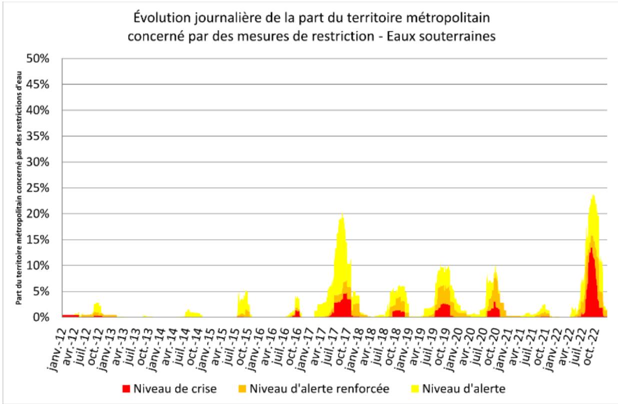
As a response, the various decision-makers involved in water resource management (e.g. French government, departmental prefects) across the country put in **place temporary restrictions for non-priority water uses**, as highlighted by the graphs below[xv]. These ranged from limits to irrigation for individuals and agriculture to bans on groundwater withdrawals, over-ground swimming pool filling and car wash[xvi].

*Daily evolution of the share of the French metropolitan territory facing restrictions on the use of:*

*Surface Water*




*Underground Water*




Source: Propluvia (2023)

**Droughts are costly**, being responsible for **€611 million worth of insurance claims on average every year** since 1989 in France[xvii]. They also participate in driving **excess mortality**, with **over 4,800 deaths attributed to heat-related events** (which droughts act as a pre-cursor to) in France in the summer of 2022[xviii].

Droughts are thus a **clear challenge** for France, and are likely to become **more extreme, frequent and longer**[xix]. This has already been reported by insurance stakeholders, with a 2023 report by the Caisse Centrale de Réassurance (CCR) highlighting that **over half (52%) of claims in France in the past decade were due to droughts**, much higher than the 42% figure for the 1982-present period[xx].

This escalation is in line with global trends, and it is thus very important that we monitor and better mitigate and adapt to droughts[xxi].

## Space provides crucial tools for drought mitigation, preparedness, and response …

**Space has a critical role to play** in helping mitigate and adapt to crises caused by climate change. Earth Observation (EO) satellites can notably help acquire **high quality and reliable longitudinal data, with high spatial and temporal resolution**, to measure trends in temperature, precipitation, sea level, river flow, soil moisture, evapotranspiration, groundwater, and cryospheric characteristics[xxii]. This is essential to **increase our understanding of the water cycle and how it is changing.**

**Example –** In a recent case study related to the EU Common Agriculture Policy Basic Payment Scheme, we found that aerial photography would only provide land use/cover monitoring imagery for one-third of the country once-a-month, whereas satellite data was now providing whole-country coverage on a weekly basis[xxiii].

Remote sensing data can also **enable the development of practical tools** that can help stakeholders plan effective mitigation and adaptation strategies (e.g. resource management, resilient infrastructure development, awareness raising)[xxiv]. R&D activities focusing on the development of hydrological models using satellite data can offer **retrospective and forecast descriptions of an extreme event**, both in space and in time. These tools are particularly useful, as they can give the opportunity to **assess the social, economic and environmental impact of an event** when exploited in concordance with other data sources.

# … including a range of selected ESA EO R&D projects …

**The European Space Agency's (ESA) EO programme has spearheaded the development and operation of satellites with the global and systemic view required to monitor and understand climate change and its effects**, supplying accurate and timely information to wide-ranging stakeholders[xxv].

On top of missions (e.g. Sentinels, Aeolus, Swarm, CryoSat, Meteosat), many **ESA EO R&D projects can help climate change mitigation efforts**, notably in water resource management (with applications for droughts). These activities are run in various components of the EO programme, i.e. FutureEO, Climate-Space, and Digital Twin Earth.

This case study focuses on 5 specific EO R&D activities (described below in 'Governance'):

- NGGM
- DT-Hydrology
- Soil Moisture
- 4DMED-Hydrology
- AI4DROUGHT

**In the following few sections, we explore how these R&D activities could be beneficial if a drought similar to that experienced by France in 2022 were to re-occur.**

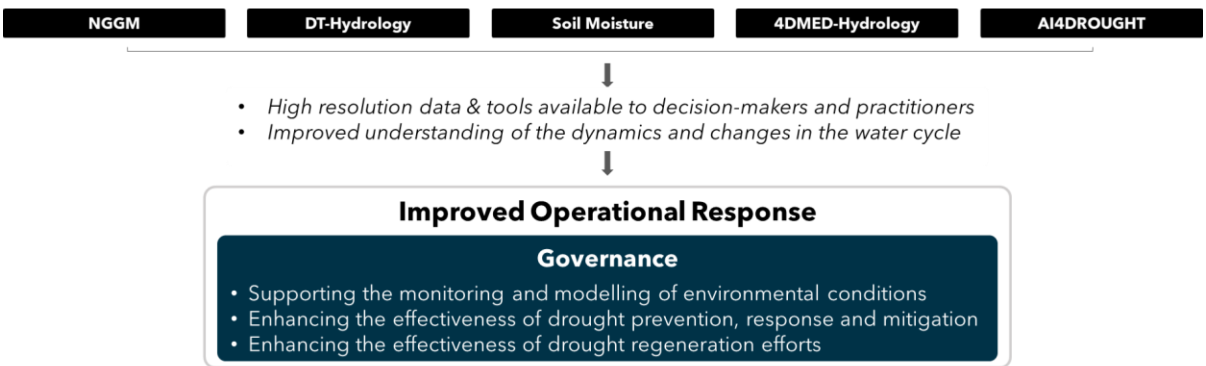
It is important to note that these are R&D projects. With a scientific focus, their aim is to develop new methodologies, concepts, platforms and technologies. By doing this, they can serve as demonstrators and pave the way for the development of operational products and services that can be broadly deployed. R&D projects thus play an **important role in enabling a wide range of benefits, directly (as outlined below) and by acting as a pre-cursor to operational applications**.

# … improving operational response to droughts …

All five ESA EO R&D activities examined provide high resolution data and/or tools on one or more elements of the water cycle (e.g. soil moisture, river discharge, evapotranspiration). By **enhancing the coverage and quality of data and tools** available to decision-makers and wider stakeholders (e.g. insurance, farmers, water managers), these activities help **increase practitioners' understanding of the water cycle and the changes occurring as a result of climate change**.

This helps improve the **operational response to drought events**. We will examine how that is the case in the following section.

*(partial) Impact chain for the selected ESA EO R&D*





The five EO R&D activities examined are particularly valuable in **supporting the monitoring and modelling of environmental conditions** and thus **enhancing the effectiveness of drought mitigation and adaptation**, as summarised below.

## NGGM

The Next-Generation Gravity Mission (NGGM) is a candidate Mission of Opportunity for ESA-NASA cooperation in the framework of MAGIC (MAss Change and Geosciences International Constellation) that is currently approaching the end of Phase A.

NGGM aims at **enabling long-term monitoring of the temporal variations of Earth's gravity field** at high temporal and spatial resolution[xxvi].

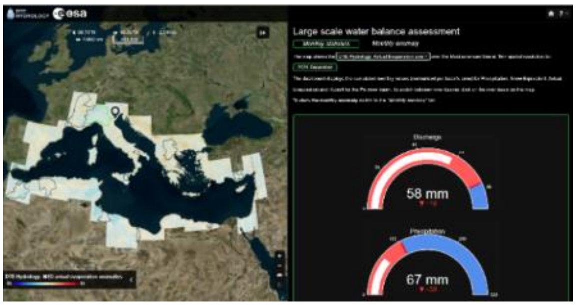
*"The MAGIC constellation will also give us gravity products at least every three to five days and they would need much less post-processing for end-users than the data we get today."*[xxvii]

For short-term products, the temporal resolution is 3 to 5 days and the spatial resolution is 300km[xxviii]. The spatial resolution increases to ~150km for monthly products (i.e. those used for drought monitoring).

> While most remote sensing data sources help derive information on water content in the first few centimetres of soil (e.g. soil moisture), they usually tend to be limited in their insight on deeper layers, where most of the water resource is stored.
>
> By detecting changes in water mass, NGGM will provide critical insights on underground water levels. This will contribute to better capturing the changes occurring in the water cycle as a result of climate change and the related mass exchange among oceans, cryosphere, land and atmosphere. NGGM data will complement other remote sensing data to significantly improve our ability to monitor and model events linked to the water cycle (e.g., droughts).
>
> This enhanced understanding of the changing dynamics of the water cycle is beneficial in two key ways:
>
> - It helps ensure a better (earlier, more targeted) response to water-related events, like droughts; and
> - It helps better understand the nature and pace of climate change-induced consequences.
>
> Beyond droughts, NGGM data will be valuable to monitor changes in the cryosphere and sea levels.

The project will be delivered by many European companies and universities[xxix].

## DT-Hydrology




DT-Hydrology seeks to develop a **Digital Twin Earth focused on the water cycle**, hydrology and its different applications[xxx].

Covering the entire Mediterranean basin, it provides high resolution retrospective data (1km) on a range of components of the water cycle.

The outputs are available on an **online platform** and include two water scenarios (in Northern Italy) to demonstrate how users can interact with the platform.

> Stakeholders can use this recreation of the water cycle to retrospectively explore large scale anomalies in the Mediterranean basin (e.g. droughts and floods) and simulate diverse environmental conditions. It offers high resolution insights on all components of the water cycle (e.g. water storage and discharge in snow, lakes, rivers, soil, groundwater), beyond just precipitation, which tends to be the most common data available at a local level.
>
> As there is no 'one size fits all' when it comes to effective drought response, decision-makers need to be able to have access to data that is specific to their area to be able to develop a local mitigation and adaptation strategy. This Digital Twin will enable them to take more appropriate decisions (e.g., restrictions, preventative measures) and better address droughts.

The project is delivered by CNR-IRPI (Italy), with support from various partners: Vienna University of Technology (TU Wien, Austria), CIMA Research Foundation (Italy), Ghent University (Belgium), Meteorological Environmental Earth Observation (MEEO, Italy), Earth Observation Data Centre (EODC, Austria), Eurac Research (Italy), and University of Bologna (Italy).

## Soil Moisture

soil moisture
cci

This project has been running since 2010 and focuses on **gathering data on soil moisture, an Essential Climate Variable (ECV)**[xxxi]. Soil moisture is key to the water cycle, being a source of water for evapotranspiration, and notably influencing hydrological and agricultural processes, runoff generation, and drought development. Building on data from 17 microwave sensors, the project has produced:

- Annually algorithmically updated global climate data record of soil moisture spanning over 40 years;
- 3 separate soil moisture products derived from active, passive and combined (active + passive) sensors; and
- 14 public releases to date, each updated with new sensors and extended time series.

> The outputs from this activity offer comprehensive high resolution (local level, every 2-3 days) data on soil moisture, a critical indicator when it comes to detecting drought risks.
>
> This data can be used in complement of data for other remote sensing and meteorological indicators (e.g. precipitation, evapotranspiration) to develop a drought

risk index, helping provide early detection so decision-makers can better mitigate and adapt to drought events.

It can also be used by third parties (e.g. Météo France) to:

- Independently validate the quality of their models in regions where they already work well; and
- Improve their models in regions where they work less well.

The project is delivered by the Earth Observation Data Centre (Austria), Technische Universität Wien (Austria), Planet, ETH Zürich (Switzerland), and Centre d'Etudes Spatiales de la Biosphère (France).

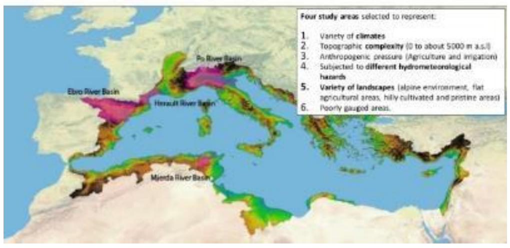
## 4DMED-Hydrology

4DMED-Hydrology is developing an **advanced, high-resolution and consistent reconstruction of the Mediterranean terrestrial water cycle** (in 4 dimensions, including time), covering precipitation, evapotranspiration, soil moisture, river discharge, snow/ice, and irrigation[xxxii]. The project involves:

- Developing high-resolution (1 km, daily, 2015–2021) EO-based datasets of the different components of the water cycle;
- Merging these datasets to obtain land water budget closure and providing a consistent high-quality merged dataset; and
- Addressing major knowledge gaps in water cycle sciences and society.

The project initially focuses on four test areas, i.e. the Po River basin in Italy, the Ebro River basin in Spain, the Hérault River basin in France and the Medjerda River basin in Tunisia – representative of different climates, topographic complexity, land use, human activities and hydrometeorological hazards of the Mediterranean region. Outputs will then be extended to the entire Mediterranean region.

4DMED-Hydrology study areas and domain




4DMED-Hydrology improves the quality of data available to stakeholders, increasing the resolution from up to 25km to <1km. This is particularly valuable in the Mediterranean basin, as its geography is very complex and changes rapidly across terrain.

Scientifically, this activity will help better understand land-atmosphere interactions (which heavily influence droughts). It will also provide key insights into how much water is being used for irrigation in the Mediterranean region, how much humans are modifying the water cycle (e.g. by looking at river discharge), and how much snow there is in the basin.

Operationally, 4DMED-Hydrology will be very valuable for drought detection and early warning, notably through its soil moisture data. With this information, decision-makers can put in place appropriate restrictions to mitigate drought impacts. Beyond droughts, 4DMED-Hydrology can be used to predict (and mitigate) landslides and floods.

The project is delivered by Vienna University of Technology (TUWIEN, Austria), Ghent University (UGent, Belgium), CIMA Research Foundation (CIMA, Italy), ESTELLUS SAS (ESTELLUS, France), Observatori de l'Ebre (OBSEBRE, Spain), Katholieke Universiteit Leuven (KULeuven, Belgium), VANDERSAT B.V. (VANDERSAT, Nederland), EURAC

Research – Accademia Europea di Bolzano (EURAC, Italy), and HydroSciences Montpellier (Institut de recherche pour le développement) (HSM, France).

## AI4DROUGHT


AI for Drought combines artificial intelligence (AI), dynamic seasonal climate prediction systems and multiple EO products (e.g. soil moisture, vegetation indices, lake levels, snow cover, burned areas) to **improve drought prediction capabilities** and increase our understanding of the causes, evolution and consequences of droughts at a seasonal timescale[xxxiii]. The project output is a model that covers Europe and parts of North Africa.

The complex dynamics between the large-scale and local drivers of droughts are not currently well represented in hydrological models. AI for Drought's model will improve the seasonal spatial and temporal predictability of droughts by providing insights on the likelihood, duration, severity and geographical extent of potential events. Importantly for users of this data, it will offer the level of confidence for each of these insights.

*Yet, despite two decades of considerable improvements, the provision of skilful seasonal precipitation predictions, especially in the extra-tropics, is notoriously challenging"*[xxxiv]

The model also provides valuable information on the impact of droughts on the different elements of the water cycle, like soil moisture, helping capture lagged effects (e.g. on vegetation) that might otherwise not be fully captured ahead of time.

Another key benefit of the model is its insights on the possible impacts of droughts, notably related to compound events (e.g. heatwaves and fires). As outlined earlier, droughts are often pre-cursor events to other extreme phenomena, and having more information on the likelihood and severity of these cascading events could substantially help minimise their detrimental impacts. This can represent a milestone in generating actionable knowledge.

Stakeholders in many sectors could benefit from the project model's insights in their drought monitoring and modelling activities, notably agriculture, insurance, government, urbanism/real estate, and anyone involved in resource management (e.g. water, forest).

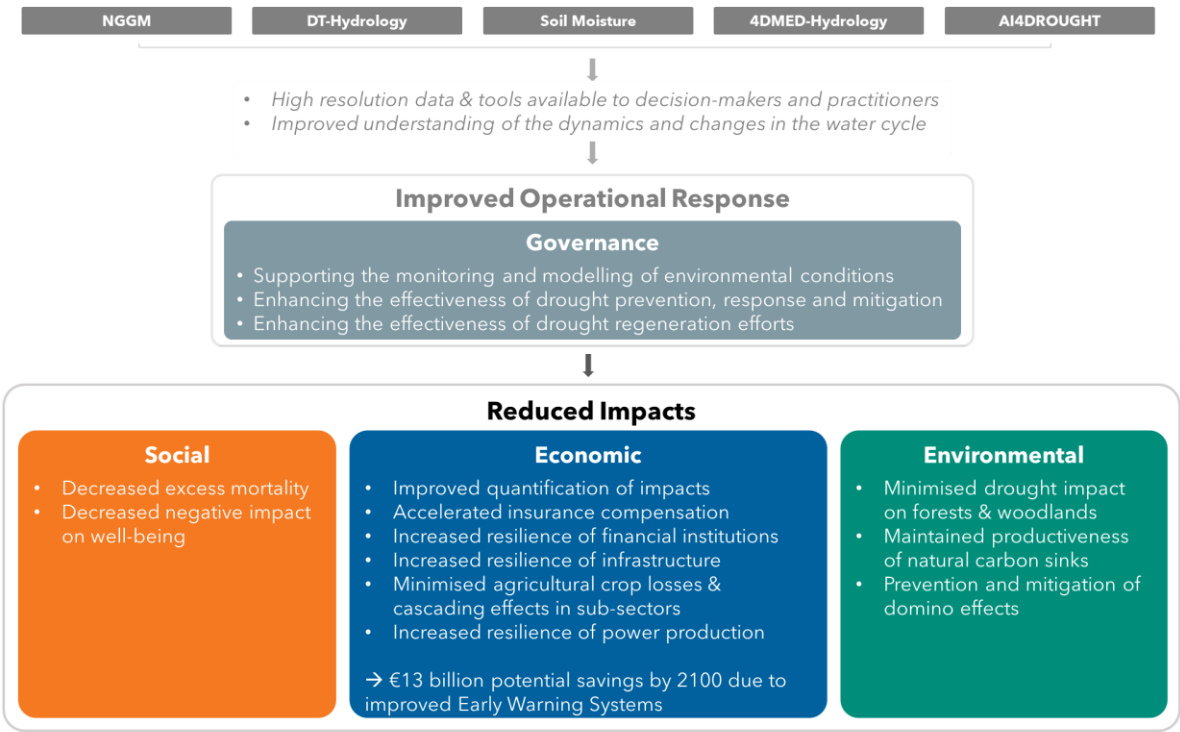
The project is delivered by Lobelia (Spain), Barcelona Supercomputing Center (Spain), and Eurecat (Spain).

Some of the examined activities can also **help guide regeneration efforts to ensure they are as effective as possible**. For example, NGGM will provide data on the state of underground water reserves, which can take months if not years to recover from a drought. The Soil Moisture project could also help track the recovery of upper ground layers, notably monitoring vegetation growing pace and patterns, and the possible impact of pathogens. Providing greater and more accurate insights on the pace at which nature is regenerating is essential, as it helps decision-makers understand if current decisions and efforts are working and whether more is needed to better recover from the drought.

# … contributing to a reduction in expected impacts of droughts …

By improving the operational response to droughts, the examined EO R&D activities may **contribute to reducing the expected social, economic and environmental impacts** of such events. We explore how that could be the case in the following few sections.

*Impact chain for the selected ESA EO R&D activities*




## Social

The examined EO R&D projects may **benefit the health and well-being of the population**. Droughts may contribute to deteriorated public health and excess mortality by driving cascading events such as heatwaves and fires[xxxv].

According to recent estimates, over 4,800 deaths have been attributed to heat in the summer of 2022 in France (i.e. 73 deaths per million), with older individuals and women particularly affected[xxxvi]. We estimate that this represents more than €15 billion in economic losses for 2022 alone[xxxvii]. A CNRS study examined the cost of excess mortality due to heat-related events over the last few decades in France and quantified it at €143 billion over the period 1974-2020[xxxviii]. **Droughts likely played a role in these deaths and economic loss by acting as a pre-cursor and exacerbator to heat events.**

Similarly, excess heat-related visits to the emergency room, visiting doctor consultations and hospitalisations were estimated to have cost €31 million between 2015 and 2019 in France[xxxix]. This is a significant underestimation, as it only considers ailments directly linked to heat events (e.g. loss of consciousness, hyperthermia, isolated fever or dehydration), excluding the numerous other health effects highlighted in the literature (i.e. on cardiorespiratory diseases, effects on occupational health, mental health, and perinatal health)[xl].

The detrimental impact on well-being also lowers the productivity of the population affected, which is estimated to cost the French economy €43 per person per day of restricted activity[xli]. Between 1974 and 2020, cumulative economic losses linked to heat-related decreased productivity stood at €13 billion (in France), 93% of which is attributable to the 2003, 2019 and 2020 heatwaves alone[xlii].

*"In the short term, at least one or two days before, we can put in place warning and prevention measures"*[xliii].

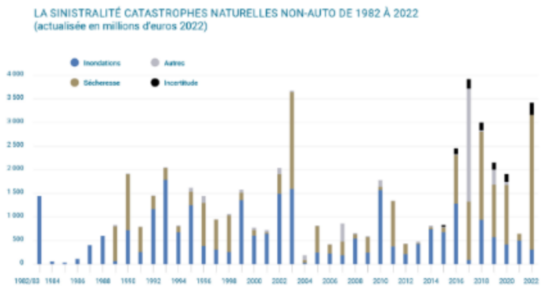
The examined EO R&D activities may **contribute to limiting detrimental impacts on well-being and excess mortality** (along with associated healthcare and economic costs) by helping decision-makers **improve their mitigation, preparedness and response to droughts and drought-related events**. For example, by getting an early-warning of a drought risk in their locality, decision-makers can put in place water restrictions to minimise the severity of the drought, organise information campaigns targeting vulnerable groups on precautionary actions during heatwaves (e.g. hydrating, staying indoors away from the sun), organise welfare checks, and strengthen resources dedicated to healthcare.

## Economic

The EO R&D projects examined are also particularly useful in **helping to estimate drought-induced economic losses**. Quantifying economic losses from droughts tends to be challenging due to their widespread and long-term impacts. Across Europe, annual economic losses linked to droughts are projected to steeply increase to €65 billion/annum by 2100 from a current estimate of €9 billion/annum (in a scenario where global temperatures increase +4 °C and there is no adaptation) [xliv].

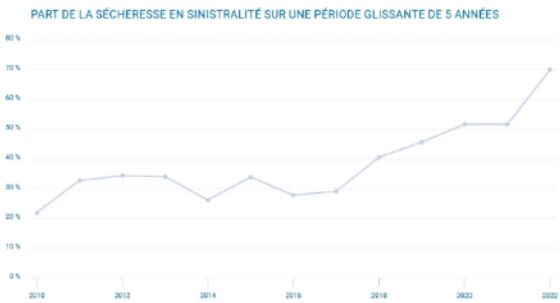
Insurance losses serve as a useful proxy measure to capture the potential financial damage droughts can inflict on the French economy. **For the 2022 droughts, the total cost of insured damages in France was estimated to stand between €2.4 billion and €2.9 billion**[xlv]. In the past few decades, drought-related insurance claims have been significantly increasing in the country, from an average of 42% of all claims since 1982 to 52% since 2012[xlvi]. A more granular breakdown is provided in the graphs below.

*Insurance claims due to natural disasters*
*By type, 1982 to 2022 (in 2022 €m)*




Source: CCR (2023)

*Share of drought claims in the past 5 years*




Source: CCR (2023)

**Clay shrinkage and swelling has been one of the key issues driving drought-induced economic losses (along with agricultural crop losses)**[xlvii]. Soil moisture heavily influences clay, a type of soil on which a lot of housing, transportation and commercial infrastructure is built[xlviii]. When droughts occur, the clay soil shrinks and expands back during recovery, causing significant damages to buildings. Damages from the phenomenon in France are estimated to have reached €16 billion in the 1989-2021 period[xlix]. France is particularly vulnerable to clay shrinkage and swelling, as much of its housing is built on clay soil, though more information on the characteristics

of each building is required (and currently lacking on a macro-scale) to fully assess the extent of the vulnerability[2] [l]. Satellite data is an important input in evaluating risk levels but *in-situ* data collection is still critical to acquire information on factors like house foundation characteristics.

> *"The phenomenon mainly affects single-family homes, and it is widespread in France: it is estimated that 48% of the national territory has medium or high exposure to clay soil shrinkage and swelling. Nationally, 10.4 million single-detached homes have a high or medium clay soil shrinkage and swelling risk, representing 54.2% of individual habitat"*[li]

While droughts clearly affect the economy at a macro-level, it is important to also highlight their micro-level economic impact. According to recent studies on European agricultural insurance mechanisms, compensation payments related to agricultural drought impacts are often delayed, as in the case of France[lii]. In 2021, farmers had to wait an average of nine months, making drought recovery (and resilience-building) challenging[liii]. These delays may be due to challenges in quantifying drought impacts for insurers[liv].

Overall, the examined EO R&D activities are particularly valuable when it comes to **helping quantify and compensate economic losses induced by droughts**. The provision of high temporal and spatial resolution data on various elements of the water cycle can contribute to better identifying vulnerabilities at a local level, helping:

- **Optimise the design of insurance policies** to best reflect risks[lv];
- Retrospectively validate damage claims for insurers, instead of relying on in-person inspections, **accelerating the compensation process**; and
- **Increase resiliency across sectors** (e.g. real estate, agriculture).

The outputs of DT-Hydrology, AI4Drought and 4DMED-Hydrology may be especially valuable due to their impact predicting / scenario functions. Soil Moisture and NGGM are also very much relevant, as they provide key longitudinal data on upper and lower ground water levels, which may help better determine where and in what conditions clay shrinkage and swelling occurs.

Similarly, the EO R&D activities examined may be **beneficial for banks, helping them determine the vulnerability of specific investments** to droughts. This is valuable, as it **supports their informed decision-making process**, helping **increase the resilience of financial institutions** and direct capital in a more resource efficient way[lvi]. This can be particularly relevant in agriculture or real estate, where a bank may decide against loaning funds for a project located in an area particularly vulnerable to droughts. Note that this is a benefit for banks, but it may negatively impact other stakeholder groups (i.e, due to decreased credit access), which itself may lead to detrimental spillover effects for the concerned area (e.g. lower productivity, population decrease)[lvii].

The examined EO R&D activities may also be helpful in **increasing drought resilience, improving recovery and accelerating insurance compensation for farmers**. The agriculture sector tends to be particularly affected by droughts[lviii]. For example, Western and Southern Europe's agriculture sector could see its outputs reduced by ~10% if

[2] This means that, in a given area, two houses may have different vulnerability levels to clay shrinkage and swelling. The figures cited in the quote thus need to be interpreted with caution: 10.4 million single-detached homes have a high or medium clay soil shrinkage and swelling risk based on their environment, but their structural characteristics will influence how much damage (if any) they sustain from the phenomenon in a drought.

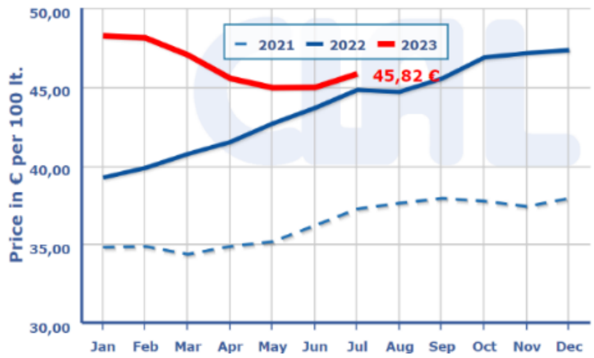
average temperatures increased by 4°C (by 2100, no adaptation), notably due to more frequent, potent and longer droughts[lix].

The nature and extent of drought risks are variable and dependent on the type of crops[lx]. For example, a 2022 study found that droughts caused significant losses of grassland to a limited number of farmers, but impacted a larger number of winter cereal farmers, though in a less severe way[lxi].

By impacting crops, droughts may lead to cascading economic effects. For example:

- In 2022, France experienced its 'lowest harvest since 1990' (-25% compared to 2021) of grain maize, the main food source of livestock[lxii].
- This may have affected livestock productivity, with milk production notably decreasing anywhere between 2% and 9% depending on regional conditions in 2022[lxiii].
- With decreasing milk supplies, prices for consumers have significantly increased across France (~23% increase between January 2022 and January 2023) [lxiv]. Given that France is the second-largest dairy producer in the European Union and exports two thirds (67%) of its dairy products to the European market, this increase could have had an impact on neighbouring countries too [lxv]. Although several geopolitical and socio-economic factors may also influence this price change, the relationship between droughts and increases in commodity prices (especially milk and meat) has been widely recognised in the scientific literature[lxvi].

*Average prices of farm-gate raw milk (France)*




Source: CLAL (2023)

The examined EO R&D activities can **help identify drought conditions at the local level**. Early warning may enable farmers and decision-makers to **better prepare, respond and mitigate drought impacts on crops**. Minimised crop losses may, in turn, **reduce (or avoid) cascading effects on agriculture sub-sectors**, like milk and meat production, overall reducing economic losses on a micro-level (farmers) and macro-level (regional, national economy). Again, projects with outputs integrating predictive / scenario functions like DT-Hydrology, AI4DROUGHT and 4DMED-Hydrology may be particularly useful in highlighting vulnerabilities and thus the need for pre-emptive resilience building.

Additionally, with increased competition and stress over water resources (globally and in France), it is important for farmers to optimise their irrigation practices[lxvii]. This is especially critical in periods of droughts, as water becomes even more limited. Soil Moisture and 4DMED-Hydrology's high resolution data is particularly beneficial for farmers, as it can help **inform effective irrigation practices**, limiting crop losses during droughts.

The EO R&D activities examined may also contribute to **increasing the resilience of power production**. Various types of power production rely on water: thermoelectric, hydro, and nuclear power plants need this precious natural resource in order to safely and reliably produce electricity, either directly or as a cooling mechanism component[lxviii]. For example, nuclear power production, which represents 63% of French electricity production, requires between 400 and 500 million cubic meters of water every year to operate[lxix]. However, droughts lead to water scarcity and tend to increase water temperatures, meaning they could result in situations where there is not enough water and/or the water is too warm to perform its function in the power production process, causing decreased power production (and in extreme cases, temporary closure of energy facilities)[lxx]. In 2022, France's leading producer of electricity (EDF) saw its power generation hit a record low, notably due to a 22% drought-induced fall in hydropower generation[lxxi].

Therefore, it is important to have a full understanding of the various elements of the water cycle, notably at the local level, to better understand drought impact on power production. **Understanding vulnerabilities or getting an early warning of water scarcity** may help decision-makers and practitioners better **prepare, respond and mitigate potential power production issues**. The examined EO R&D activities may thus be valuable due to their modelling features and high resolution data of various (or all) elements of the water cycle.

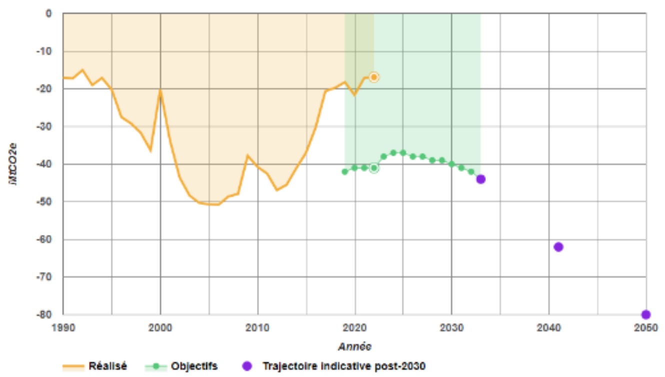
## Environmental

The EO R&D activities examined could also be **particularly beneficial for forests and woodlands management**. Droughts are the primary determinant of forest health[lxxii]. They hinder the growth of trees and photosynthesis, leading to a significant reduction in the productivity of forests, overall limiting their ability to act as a carbon sink[lxxiii]. Beyond lower productivity, droughts can lead to cascading events like fires, which can result in the destruction of forests (important carbon sinks and natural habitats for numerous species).

*"The decline in carbon sinks in recent years, particularly in forests, is linked to droughts (reinforced by climate change), to fires and to diseases"*[lxxiv]

As highlighted in the graph below, carbon sequestration has been rapidly falling in the past two decades, with some regions (e.g. Grand Est, Hauts-de-France and Corsica) seeing their forests emit carbon dioxide instead of absorbing it[lxxv]. This is particularly problematic given forests play a major role in France's National Low Carbon Strategy. In 2022, sequestration was nearly 60% below its target for 2022 (16.9 MtCO2e realised, 41 MtCO2e targeted)[lxxvi]. A recent report by the French Academy of Science highlighted that, as a consequence, national $CO_2$ objectives cannot be met with the current strategy, which must thus be revised[lxxvii].

*Emissions linked to land use, land use change and forestry in France, including carbon sinks.*




Source: Observatoire Climat Energie (2023)

4DMED-Hydrology, DT-Hydrology, Soil Moisture and AI4Drought can be particularly beneficial for stakeholders involved in forest and woodland management, as they provide **data at the local level and capture insights in the upper ground layers**. This can help them better anticipate and mitigate drought conditions, **minimising the impact of such events on forests' health and productivity**. It can also **support regeneration efforts**, by monitoring their effectiveness and helping detect whether anything is hindering recovery (e.g. pathogens). AI4Drought could also be valuable in **predicting/simulating cascading events**, like fires, which could further damage the health and productivity of forests and woodland. Again, this provides decision-makers and practitioners with an early warning, meaning they are able to take mitigation measures to avoid (or minimise) further damages.

> *"When droughts are repeated, trees are no longer able to recover and they end up weakening. These situations have been repeated since 2018, with successive heatwaves and dry summers. We had a 50% surplus in tree mortality over the last decade compared to the 2000s"*[lxxviii]

By helping to prevent and minimise the impact of repeated droughts on forests and woodlands, the EO R&D projects examined in this Case Study contribute to **ensuring that these carbon sinks continue to be productive tools in reducing $CO_2$ emissions, thus helping slow down climate change**.

Similarly, the examined projects can **help mitigate the domino effects** stemming from droughts. For example:[lxxix]

- Low soil moisture may kill plants and thus lead to habitat loss for certain species of animals and insects. This can result in their death, subsequently affecting the species relying on them for nutrition. This disruption of the food web can, in turn, hinder the survival of the most vulnerable individuals within a species, including young offspring and juveniles, and alter breeding cycles. Overall, this can result in migration, temporary loss and in extreme cases, the extinction of local species.
- Reduced soil moisture can limit the photosynthesis of vegetation, affecting the carbon cycle and balance. This can lead to the deterioration of soil quality, increasing soil erosion and thus habitat loss.
- Depleted ground water can result in lower water levels in rivers, lakes, ponds, wetlands and aquifers, which may reduce the available habitat for a wide range of species. It can also lead to natural triggers for migration and spawning (e.g. sudden floods) being missed, affecting species lifecycles over the coming seasons or years.
- Low soil moisture and water levels can lead to a reduction in the vegetation on the edges of rivers and lakes, decreasing the shading and cooling effects on the water, resulting in water temperature increasing. This can affect the wildlife and also lead to the proliferation of algae.
- Lower water levels can lead to the increased concentration of wastewater pollutants (e.g. phosphates, nitrates, pharmaceuticals, organic chemicals) and nutrients (eutrophication), promoting algal bloom and intensifying stress on the wildlife.
- Low water flow can reduce the gas exchange with the atmosphere, resulting in low dissolved oxygen levels, supporting the growth of algae.
- The combination of elevated nutrient concentration, water temperatures, low river flow and sunlight can lead to algal bloom, which shade out and outcompete submerged aquatic plants, hindering their survival. This, in turn, can affect freshwater ecosystems and biodiversity, which can result in impacts on terrestrial birds and mammals.

The systemic perspective of EO R&D activities (e.g. NGGM, DT-Hydrology, 4DMED-Hydrology, AI4Drought) may be particularly valuable in helping **identify what dynamics of the water cycle will be the most affected** by a drought event, **how they regenerate**, and thus **which areas and habitats are the most vulnerable**. The high spatial resolution of their data (e.g. ground water levels, water storage discharge, evapotranspiration) can then offer **in-depth insights at a local**

**level** to help decision-makers and practitioners better address the impact of droughts and **avoid domino effects on ecosystems and ecosystem services**. AI4Drought's predictions on drought impact on compound events (e.g. heatwaves) could also be particularly beneficial in avoiding cascading damages.

## … which could save Europe € billions per annum

As highlighted in earlier sections, the analysed EO R&D projects offer substantial improvements in data quality, coverage, and visualisation for key elements of the water cycle, which is fundamental for the **development of early warning systems (EWS)**. These allow decision-makers to better forecast droughts and related phenomena (e.g. heatwaves, subsidence from clay shrinkage), helping improve preparedness and resilience, ultimately reducing drought-related costs.

**Quantifying the benefits of the EO R&D activities examined in this Case Study is challenging**, as they have not yet been operationalised. However, we can offer a high-level indicative estimation of benefits in a hypothetical operational scenario where improved water cycle data from the activities enables an enhanced early warning system (EWS).

**Example –** 4DMED-Hydrology's hydrological datasets provide publicly available data for most water cycle variables. This EO data, combined with in-situ and model data, is capable of providing accurate reconstructions of the Mediterranean land-atmosphere interactions and processes. This can be leveraged to inform (and improve) EWS.

To provide an illustrative quantification of potential cost-savings from improved EWS, leveraging these EO R&D activities, we consider three impact scenarios, corresponding to three previously-mentioned drought loss estimates **for Europe** (p.3):

- **Present day** scenario considers a recent estimation (2020) of annual drought losses across European countries: **€9 billion of losses across Europe per annum**[lxxx].
- **+3°C projection by 2100** scenario considers projections of yearly drought damages in 2100 across European countries for a +3°C temperature increase in the absence of adaptation measures: **€45 billion of losses across Europe per annum**[lxxxi].
- **+4°C projection by 2100** scenario considers projections of yearly drought damages in 2100 across European countries for a +4°C temperature increase in the absence of adaptation measures: **€65 billion of losses across Europe per annum**.

When defining the loss reduction potential from EWS, we considered estimates presented in the literature. In particular, a 2014 EUMETSAT report found that issuing 48-hour early warnings could decrease impact costs of forest fires, snow, heatwaves, cold spells and windstorms by 33%, and reduce flooding damages by 25%[lxxxii]. Informed by this study, but treating as an upper bound for analytical conservatism, we derived estimates for the potential percentage cost savings driven by EWS leveraging ESA EO R&D data improvements. Our analysis is based on the following cost reduction percentages:

- **Present day** scenario, we consider an enhanced EWS to contribute to a **10% reduction** in losses: this is a more conservative assumption than the EUMETSAT study to account for the domino and compound effects that droughts generate and the longer timeframe in which drought conditions materialise[lxxxiii].
- **+3°C and +4°C by 2100** scenarios, we consider an enhanced EWS to contribute to a **20% reduction** in losses: this is still a more conservative assumption than in the EUMETSAT study, but higher than the present day scenario to account for expected technological improvements (e.g. artificial intelligence, digital twins, next generation satellites) and greater scientific understanding of climate systems by 2100.

The table below presents potential drought cost saving estimates of an enhanced EWS for each scenario, based on the above cost-reduction assumptions and loss estimates across Europe per annum.

*Possible drought-related cost savings across Europe per annum from an enhanced EWS*[lxxxiv]

| Drought scenario | Losses without EWS (in Europe p.a.) | EWS Impact Reduction | Losses with EWS (in Europe p.a.) | Savings due to EWS |
|---|---|---|---|---|
| Present day | €9 billion | 10% | €8 billion | **€1 billion** |
| +3°C projection by 2100 | €45 billion | 20% | €36 billion | **€9 billion** |
| +4°C projection by 2100 | €65 billion | 20% | €52 billion | **€13 billion** |

While the activities examined are not operationalised yet and are still R&D in nature, they already have **potential to support the development of enhanced EWS by improving water cycle data quality, coverage and visualisation**. Although the **presented estimates are to be interpreted with caution** (due to assumptions that are subject to the influence of wide-ranging factors), it is clear that the ESA EO R&D activities examined in this Case Study **could contribute to significantly reducing losses from droughts across Europe in the future**.

... now you **know.**

# End notes


[i] IPCC (2022). *Sixth Assessment Report*. https://www.ipcc.ch/assessment-report/ar6/; Stockholm Resilience Centre (n.d.). *The nine planetary boundaries*. https://www.stockholmresilience.org/research/planetary-boundaries/the-nine-planetary-boundaries.html; Stockholm Resilience Centre (2023). *Planetary boundaries*. https://www.stockholmresilience.org/research/planetary-boundaries.html

[ii] UCAR (n.d.). *The Water Cycle and Climate Change*. https://scied.ucar.edu/learning-zone/climate-change-impacts/water-cycle-climate-change#:~:text=Climate%20change%20affects%20evaporation%20and,causing%20more%20precipitation%2C%20on%20average.; Nature Water (2023). *How climate change alters the water cycle*. https://www.nature.com/articles/s44221-023-00104-6; Abbott, B. W., et al. (2019). *Human domination of the global water cycle absent from depictions and perceptions*. Nature Geoscience (12), pp. 533-540.; USGS (2022). *The Water Cycle*. https://www.usgs.gov/special-topics/water-science-school/science/water-cycle

[iii] Water Information System for Europe (n.d.). *Water resources of Europe*. https://water.europa.eu/freshwater/europe-freshwater/freshwater-themes/water-resources-europe

[iv] European Commission (2020). *Impacts of climate change on droughts*. https://joint-research-centre.ec.europa.eu/system/files/2020-09/07_pesetaiv_droughts_sc_august2020_en.pdf; Walsh, L. (2022). *What are the effects of drought?*. https://www.cam.ac.uk/stories/drought-and-climate-change; National Drought Mitigation Center (n.d.). *How does drought affect our lives?*. https://drought.unl.edu/Education/DroughtforKids/DroughtEffects.aspx

[v] European Commission (2020). *Impacts of climate change on droughts*. https://joint-research-centre.ec.europa.eu/system/files/2020-09/07_pesetaiv_droughts_sc_august2020_en.pdf; Walsh, L. (2022). *What are the effects of drought?*. https://www.cam.ac.uk/stories/drought-and-climate-change; National Drought Mitigation Center (n.d.). *How does drought affect our lives?*. https://drought.unl.edu/Education/DroughtforKids/DroughtEffects.aspx

[vi] European Commission. (2020). *Impact of climate change on droughts*. https://joint-research-centre.ec.europa.eu/system/files/2020-09/07_pesetaiv_droughts_sc_august2020_en.pdf

[vii] Naumann, G. et al. (2021). *Increased economic drought impacts in Europe with anthropogenic warming*. https://www.nature.com/articles/s41558-021-01044-3

[viii] Sutanto, et al. (2020). *Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale*. Environment International (134). https://www.sciencedirect.com/science/article/pii/S0160412019308530

[ix] Sutanto, et al. (2020). *Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale*. Environment International (134). https://www.sciencedirect.com/science/article/pii/S0160412019308530

[x] European Environment Agency (2023). *Extreme weather: floods, droughts and heatwaves*. https://www.eea.europa.eu/en/topics/in-depth/extreme-weather-floods-droughts-and-heatwaves

[xi] Météo-France (2023). *2022, année la plus chaude en France*. https://meteofrance.com/actualites-et-dossiers/actualites/2022-annee-la-plus-chaude-en-france

[xii] Météo-France (2023). *2022, année la plus chaude en France*. https://meteofrance.com/actualites-et-dossiers/actualites/2022-annee-la-plus-chaude-en-france; European Drought Observatory (2023). *Compare Layers*. https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1138#

[xiii] Météo-France (2023). *2022, année la plus chaude en France*. https://meteofrance.com/actualites-et-dossiers/actualites/2022-annee-la-plus-chaude-en-france

[xiv] Météo-France (2023). *Eté 2022 : les épisodes de chaleur attribués au changement climatique*. https://meteofrance.com/actualites-et-dossiers-0/ete-2022-les-episodes-de-chaleur-attribues-au-changement-climatique

[xv] Gouvernement (2023). *Sécheresse en France*. https://www.ecologie.gouv.fr/secheresse-economiser-leau; https://propluvia.developpement-durable.gouv.fr/propluviapublic/

[xvi] Préfet d'Ille-et-Vilaine (2022). *L'Ille-et-Vilaine est placé en crise sécheresse*. https://www.ille-et-vilaine.gouv.fr/contenu/telechargement/59616/402440/file/Affiche+crise+secheresse_pref35.pdf; Propulvia (2023). *Le site de l'information sécheresse du Gouvernement*.

[xvii] CCR (2023). *Les catastrophes naturelles en France: Bilan 1982-2022*. https://www.ccr.fr/documents/35794/1190256/BILAN+Cat+Nat+2022_HD_05.07.2023.pdf/dff71226-f79b-9cb4-a25b-3bf4878e9345?t=1688568915554

[xviii] Ballester, J., et al. (2023). *Heat-related mortality in Europe during the summer of 2022*. Nature Medicine. 29. pp. 1857-1866. https://www.nature.com/articles/s41591-023-02419-z

[xix] European Commission (2020). *Global warming and drought impacts in the EU*. https://joint-research-centre.ec.europa.eu/system/files/2020-05/pesetaiv_task_7_drought_final_report.pdf

[xx] CCR (2023). *Les catastrophes naturelles en France: Bilan 1982-2022*. https://www.ccr.fr/documents/35794/1190256/BILAN+Cat+Nat+2022_HD_05.07.2023.pdf/dff71226-f79b-9cb4-a25b-3bf4878e9345?t=1688568915554

[xxi] EU Copernicus (2022). *OBSERVER: A wrap-up of Europe's summer 2022 heatwave*. https://www.copernicus.eu/en/news/news/observer-wrap-europes-summer-2022-heatwave

[xxii] ESA (n.d.). *Role of EO in Understanding Climate Change*. https://climate.esa.int/en/evidence/role-eo-understanding-climate-change/; Nature Water (2023). *Measuring water from space*. https://www.nature.com/articles/s44221-023-00042-3; Reager, J. (2021). *Progress in monitoring the global water cycle from space*. https://ui.adsabs.harvard.edu/abs/2021cosp...43E..29R/abstract

[xxiii] know.space (2023). *The Case for Space*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1170076/the_case_for_space.pdf

[xxiv] European Commission (2019). *EU Space for Climate Action*. https://www.copernicus.eu/sites/default/files/2020-02/PRINT%20EU%20Space%20program%2013.pdf; West, H. (2019). *Remote sensing for drought monitoring & impact assessment: Progress, past challenges and future opportunities*. Remote Sensing of Environment. 232. https://www.sciencedirect.com/science/article/abs/pii/S0034425719303104

[xxv] ESA (n.d.). *Earth Observation*. https://www.esa.int/About_Us/Earth_observation

[xxvi] Massotti, L., et al. (2023). *Next Generation Gravity Mission design activities within the MAGIC - MAss Change and Geoscience International – Constellation*. https://meetingorganizer.copernicus.org/EGU23/EGU23-14482.html

[xxvii] ESA (2023). *The future of gravity is MAGIC*. https://www.esa.int/Applications/Observing_the_Earth/FutureEO/The_future_of_gravity_is_MAGIC

[xxviii] ESA (2023). *Next Generation Gravity Mission (NGGM): Mission Requirement Document*.

[xxix] Technical University Munich (n.d.). *Simulation studies for a Mass change And Geosciences International Constellation (MAGIC)*. https://www.asg.ed.tum.de/en/iapg/magic/; Massotti, L., et al. (2022). *Next Generation Gravity Mission design activities within the Mass Change and Geoscience International Constellation*. https://indico.esa.int/event/416/contributions/7507/attachments/4913/7529/Clean%20Space%20Industrial%20Days_NGGM%20w_video_v3.pdf

[xxx] National Research Council of Italy (n.d.). *DTE Hydrology (Evolution)*. http://hydrology.irpi.cnr.it/projects/dte-hydrology/#:~:text=The%20European%20Space%20Agency%20(ESA,hydrology%20and%20its%20different%20applications

[xxxi] ESA (n.d.). *Soil Moisture*. https://climate.esa.int/en/projects/soil-moisture/

[xxxii] ESA (n.d.). *4DMED-Hydrology*. https://eo4society.esa.int/projects/4dmed-hydrology/#:~:text=4DMED%2DHydrology%20aims%20at%20developing,from%20the%20ESA%2DCopernicus%20missions; *4DMED-Hydrology* (n.d.). Project Summary. https://www.4dmed-hydrology.org/

[xxxiii] AI for Drought (n.d.). *Our research*. https://www.ai4drought.com/#our-research

[xxxiv] AI for Drought (n.d.). *Our research*. https://www.ai4drought.com/#our-research

[xxxv] Sutanto, et al. (2020). *Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale*. Environment International (134). https://www.sciencedirect.com/science/article/pii/S0160412019308530

[xxxvi] Ballester, J. (2023). *Heat-related mortality in Europe during the summer of 2022*. https://www.nature.com/articles/s41591-023-02419-z

[xxxvii] Téhard, B. (2020). *Value of a QALY for France: A New Approach to Propose Acceptable Reference Values*. https://www.sciencedirect.com/science/article/pii/S1098301520301881

[xxxviii] Chanel, O. & Vinchon, T. (2023). *Les canicules : un coup de chaud pour l'économie*. https://lejournal.cnrs.fr/nos-blogs/dialogues-economiques/les-canicules-un-coup-de-chaud-pour-leconomie

[xxxix] Chanel, O. & Vinchon, T. (2023). *Les canicules : un coup de chaud pour l'économie*. https://lejournal.cnrs.fr/nos-blogs/dialogues-economiques/les-canicules-un-coup-de-chaud-pour-leconomie

[xl] WHO (n.d.) *Heat and Health*. https://www.who.int/news-room/fact-sheets/detail/climate-change-heat-and-health; Mason, H., et al. (2022). *Systematic review of the impact of heatwaves on health service demand in Australia*. BMC Health Services Research. 22. https://bmchealthservres.biomedcentral.com/articles/10.1186/s12913-022-08341-3

[xli] Chanel, O. & Vinchon, T. (2023). *Les canicules : un coup de chaud pour l'économie*. https://lejournal.cnrs.fr/nos-blogs/dialogues-economiques/les-canicules-un-coup-de-chaud-pour-leconomie

[xlii] Chanel, O. & Vinchon, T. (2023). *Les canicules : un coup de chaud pour l'économie*. https://lejournal.cnrs.fr/nos-blogs/dialogues-economiques/les-canicules-un-coup-de-chaud-pour-leconomie

[xliii] Chanel, O. & Vinchon, T. (2023). *Les canicules : un coup de chaud pour l'économie*. https://lejournal.cnrs.fr/nos-blogs/dialogues-economiques/les-canicules-un-coup-de-chaud-pour-leconomie. Quote translated from French.

[xliv] Naumann, G. et al. (2021). *Increased economic drought impacts in Europe with anthropogenic warming*. https://www.nature.com/articles/s41558-021-01044-3

[xlv] CCR (2023). *Les Catastrophes Naturelles en France*. https://www.ccr.fr/recherche?p_p_id=com_liferay_portal_search_web_search_results_portlet_SearchResultsPortlet_INSTANCE_q7ALUoLhxDZe&p_p_lifecycle=0&p_p_state=maximized&p_p_mode=view&_com_liferay_portal_search_web_search_results_portlet_SearchResultsPortlet_INSTANCE_q7ALUoLhxDZe_mvcPath=%2Fview_content.jsp&_com_liferay_portal_search_web_search_results_portlet_SearchResultsPortlet_INSTANCE_q7ALUoLhxDZe_assetEntryId=1190453&_com_liferay_portal_search_web_search_results_portlet_SearchResultsPortlet_INSTANCE_q7ALUoLhxDZe_type=document&p_l_back_url=%2Frecherche%3Fq%3Dsecheresse%26delta%3D50

[xlvi] CCR (2023). *Les Catastrophes Naturelles en France*. https://www.ccr.fr/recherche?p_p_id=com_liferay_portal_search_web_search_results_portlet_SearchResultsPortlet_INSTANCE_q7ALUoLhxDZe&p_p_lifecycle=0&p_p_state=maximized&p_p_mode=view&_com_liferay_portal_search_web_search_results_portlet_SearchResultsPortlet_INSTANCE_q7ALUoLhxDZe_mvcPath=%2Fview_content.jsp&_com_liferay_portal_search_web_search_results_portlet_SearchResultsPortlet_INSTANCE_q7ALUoLhxDZe_assetEntryId=1190453&_com_liferay_portal_search_web_search_results_portlet_SearchResultsPortlet_INSTANCE_q7ALUoLhxDZe_type=document&p_l_back_url=%2Frecherche%3Fq%3Dsecheresse%26delta%3D50

[xlvii] CCR (2023). *Rapport Scientifique 2022*. https://ccr.foleon.com/rapport-scientifique-ccr-2022/rapport-scientifique-ccr-2022/

[xlviii] British Geological Survey (n.d.). *Swelling and shrinking soils*. https://www.bgs.ac.uk/geology-projects/shallow-geohazards/clay-shrink-swell/

[xlix] Barthelemy, S. (2023). *A new drought index fitted to clay shrinkage induced subsidence over France: benefits of interactive leaf area index*. https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1366/

[l] Commmission des Finances (2022). *La Sécheresse ébranle les fondations du régime catnat*. https://www.senat.fr/rap/r22-354/r22-354-syn.pdf

[li] Commmission des Finances (2022). *La Sécheresse ébranle les fondations du régime catnat*. https://www.senat.fr/rap/r22-354/r22-354-syn.pdf Quote translated from French.
[lii] Schwarze, R. (2022). *Climate Insurance for Agriculture in Europe: On the Merits of Smart Contracts and Distributed Ledger Technologies*. https://www.mdpi.com/1911-8074/15/5/211; Faye, M. (2021). *Saône-et-Loire : les Jeunes Agriculteurs interpellent le ministre sur le retard de l'indemnisation de la sécheresse*. https://france3-regions.francetvinfo.fr/bourgogne-franche-comte/saone-et-loire-les-jeunes-agriculteurs-interpellent-le-ministre-sur-le-retard-de-l-indemnisation-de-la-secheresse-1958773.html
[liii] Pistorius, M. (2021). *Macron announces new French crop insurance scheme*. https://www.euractiv.com/section/agriculture-food/news/macron-announces-new-french-crop-insurance-scheme/
[liv] Schwarze, R. (2022). *Climate Insurance for Agriculture in Europe: On the Merits of Smart Contracts and Distributed Ledger Technologies*. https://www.mdpi.com/1911-8074/15/5/211
[lv] Pistorius, M. (2021). *Macron announces new French crop insurance scheme*. https://www.euractiv.com/section/agriculture-food/news/macron-announces-new-french-crop-insurance-scheme/
[lvi] UN Environment Programme (2017). *Drought Stress Testing Tool*. https://www.unepfi.org/industries/banking/drought-stress-testing-tool/
[lvii] Rajan, R. G. & Ramcharan, R. (2023). *Finance and Climate Resilience: Evidence From the Long 1950s US Drought*. https://bfi.uchicago.edu/insight/research-summary/finance-and-climate-resilience-evidence-from-the-long-1950s-us-drought/
[lviii] European Environment Agency (2023). *Extreme weather: floods, droughts and heatwaves*. https://www.eea.europa.eu/en/topics/in-depth/extreme-weather-floods-droughts-and-heatwaves; European Commission (2020). *Global warming and drought impacts in the EU*. https://joint-research-centre.ec.europa.eu/system/files/2020-05/pesetaiv_task_7_drought_final_report.pdf
[lix] Naumann, G., et al. (2021). *Increased economic drought impacts in Europe with anthropogenic warming*. https://www.nature.com/articles/s41558-021-01044-3
[lx] Kapsambelis, D. (2022). *Modélisation d'événements climatiques extrêmes sur les productions agricoles à horizon 2050: Application à la gestion économique du risqué*. https://theses.hal.science/tel-03953483
[lxi] Kapsambelis, D. (2022). *Modélisation d'événements climatiques extrêmes sur les productions agricoles à horizon 2050: Application à la gestion économique du risqué*. https://theses.hal.science/tel-03953483
[lxii] Durisin, M. (2022). *Smallest French Corn Crop Since 1990 Shows Drought's Huge Toll*. https://www.bloomberg.com/news/articles/2022-09-13/smallest-french-corn-crop-since-1990-shows-drought-s-huge-toll#xj4y7vzkg; Euronews (2022). *'Absolute emergency': 'Billions' needed to compensate drought losses in France*. https://www.euronews.com/2022/08/25/absolute-emergency-billions-needed-to-compensate-drought-losses-in-france
[lxiii] TF1 Info (2022). *"Historic" drought and scorching summer: effects until 2023 on agriculture?*. https://www.tf1info.fr/environnement-ecologie/secheresse-historique-et-ete-caniculaire-des-effets-jusqu-en-2023-sur-l-agriculture-2234248.html
[lxiv] CLAL (2023). *Farm-gate milk prices, France*. https://www.clal.it/en/?section=latte_francia
[lxv] La filière laitière (n.d.) *The French dairy industry in figures*. https://www.filiere-laitiere.fr/en/key-figures/50-facts-about-french-dairy-industry; La filière laitière (n.d.) *France: a strong export business*. https://www.filiere-laitiere.fr/en/filiere-laitiere/market-expanding-through-exports
[lxvi] Durisin, M. (2022). *What Europe's Drought Means for the Price of Meat and Milk*. https://www.bloomberg.com/news/articles/2022-08-12/what-europe-s-drought-means-for-the-price-of-meat-and-milk#xj4y7vzkg
[lxvii] Mantovani, A. (2023). *French People Are Fighting Over Giant Pools of Water*. https://www.theatlantic.com/science/archive/2023/06/water-mega-basins-reservoirs-france-drought/674313/
[lxviii] Scigacz, M. (2023). *Sécheresse : le manque d'eau peut-il mettre la France en panne électrique?* https://www.francetvinfo.fr/meteo/secheresse/secheresse-le-manque-d-eau-peut-il-mettre-la-france-en-panne-electrique_5790950.html. Quote translated from French.
[lxix] Scigacz, M. (2023). *Sécheresse : le manque d'eau peut-il mettre la France en panne électrique?* https://www.francetvinfo.fr/meteo/secheresse/secheresse-le-manque-d-eau-peut-il-mettre-la-france-en-panne-electrique_5790950.html.
[lxx] Schroders (2022). *The impact of droughts on the energy mix*. https://www.schroders.com/en-gb/uk/institutional/insights/the-impact-of-droughts-on-the-energy-mix/
[lxxi] Enerdata (2023). *EDF's power generation in France reached a record low in 2022*. https://www.enerdata.net/publications/daily-energy-news/edfs-power-generation-france-reached-record-low-2022.html
[lxxii] Académie des Sciences (2023). *Les forêts françaises face au changement climatique*. https://www.academie-sciences.fr/pdf/rapport/060623_foret.pdf
[lxxiii] Office National des Forêts (n.d.). *Les forêts françaises face à la sécheresse*. https://www.onf.fr/vivre-la-foret/+/191f::les-forets-francaises-face-la-secheresse.html; Académie des Sciences (2023). *Les forêts françaises face au changement climatique*. https://www.academie-sciences.fr/pdf/rapport/060623_foret.pdf
[lxxiv] Le Monde (2023). Climat : la France a diminué ses émissions de $CO_2$ en 2022, mais les forêts et les sols ont moins absorbé que prévu. https://www.lemonde.fr/planete/article/2023/09/14/climat-la-france-a-diminue-ses-emissions-en-co2-en-2022-mais-les-forets-et-les-sols-ont-moins-absorbe-que-prevu_6189331_3244.html#:~:text=%C2%AB%20La%20baisse%20des%20puits%20carbone,secteur%20sont%20difficiles%20%C3%A0%20%C3%A9valuer. Quote translated from French.
[lxxv] Observatoire Climat Energie (2023). *UTCATF en France*. https://www.observatoire-climat-energie.fr/climat/global/emissions-nettes/utcatf/; Vasseur, J. (2023). *Réchauffement climatique : les forêts du Grand Est n'assurent plus leur rôle de puits de carbone, pire elles émettent du CO2*. https://france3-regions.francetvinfo.fr/grand-est/les-forets-du-grand-est-n-assurent-plus-leur-role-de-puits-de-carbone-pire-elles-emettent-du-co2-2800913.html

[lxxvi] Observatoire Climat Energie (2023). *UTCATF en France*. https://www.observatoire-climat-energie.fr/climat/global/emissions-nettes/utcatf/; Vasseur, J. (2023). *Réchauffement climatique : les forêts du Grand Est n'assurent plus leur rôle de puits de carbone, pire elles émettent du CO2*. https://france3-regions.francetvinfo.fr/grand-est/les-forets-du-grand-est-n-assurent-plus-leur-role-de-puits-de-carbone-pire-elles-emettent-du-co2-2800913.html
[lxxvii] Académie des Sciences (2023). *Les forêts françaises face au changement climatique*. https://www.academie-sciences.fr/pdf/rapport/060623_foret.pdf
[lxxviii] Vasseur, J. (2023). *Réchauffement climatique : les forêts du Grand Est n'assurent plus leur rôle de puits de carbone, pire elles émettent du CO2*. https://france3-regions.francetvinfo.fr/grand-est/les-forets-du-grand-est-n-assurent-plus-leur-role-de-puits-de-carbone-pire-elles-emettent-du-co2-2800913.html. Quote translated from French.
[lxxix] UK Centre for Ecology & Hydrology (2022). *The impacts of drought on water quality and wildlife*. https://www.ceh.ac.uk/news-and-media/blogs/impacts-drought-water-quality-and-wildlife#:~:text=Impacts%20on%20land%2Dbased%20wildlife,and%20native%20flora%20and%20fauna; European Environmental Agency (2021). *Ecological status of surface waters in Europe*. https://www.eea.europa.eu/ims/ecological-status-of-surface-waters; futurearth (2020). *Main challenges and drivers of biodiversity loss in France: a literature review*. https://futureearth.org/wp-content/uploads/2020/12/The-Post-2020-Biodiversity-Targets-and-the-SDGs-in-France-What-Pathways-to-Achieve-Them.pdf; European Environment Agency (2023). *Drought impact on ecosystems in Europe (8th EAP)*. https://www.eea.europa.eu/ims/drought-impact-on-ecosystems-in-europe
[lxxx] European Commission. (2020). *Impact of climate change on droughts*. https://joint-research-centre.ec.europa.eu/system/files/2020-09/07_pesetaiv_droughts_sc_august2020_en.pdf;
[lxxxi] Naumann, G. et al. (2021). *Increased economic drought impacts in Europe with anthropogenic warming*. https://www.nature.com/articles/s41558-021-01044-3
[lxxxii] EUMETSAT. (2023). *The social and economic benefits of EPS-AEOLUS and EPS-Sterna*.
[lxxxiii] Logar, I. & Van den Bergh, J. (2012). *Methods to Assess Costs of Drought Damages and Policies for Drought Mitigation and Adaptation: Review and Recommendations*. https://link.springer.com/article/10.1007/s11269-012-0119-9

[lxxxiv] Sources for "Losses without warning" estimates: European Commission. (2020). *Impact of climate change on droughts*. https://joint-research-centre.ec.europa.eu/system/files/2020-09/07_pesetaiv_droughts_sc_august2020_en.pdf; European Commission. (2020). *Impact of climate change on droughts*. https://joint-research-centre.ec.europa.eu/system/files/2020-09/07_pesetaiv_droughts_sc_august2020_en.pdf