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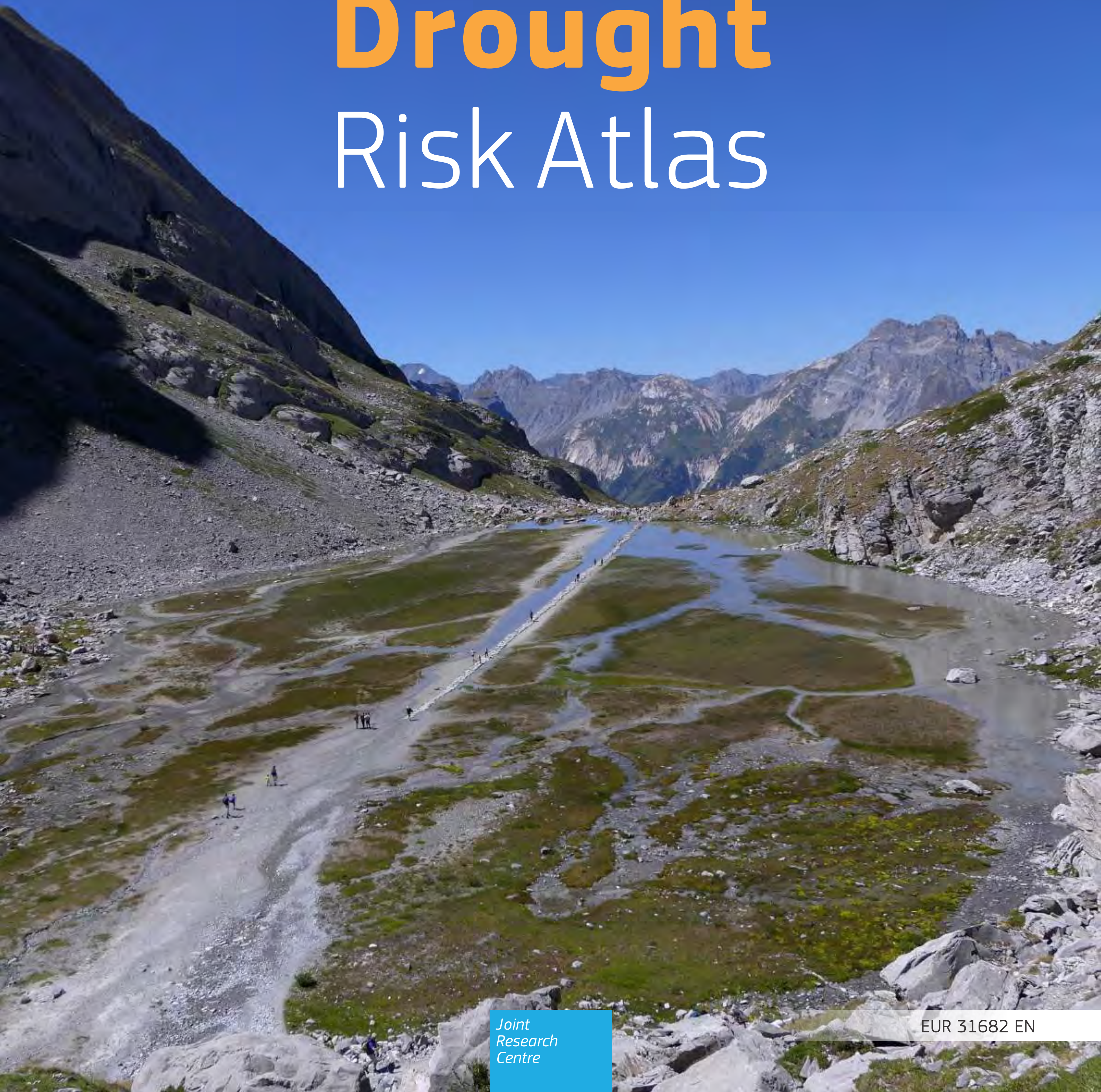

European **Drought** Risk Atlas

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Pag. 9: Figure 1: The systemic nature of drought risks and impacts (Hagenlocher et al. 2023).

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European **Drought** Risk Atlas

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ABSTRACT

In recent years, droughts have had substantial impacts on nearly all regions of the EU, affecting several critical systems such as agriculture, water supply, energy, river transportation, and ecosystems. These impacts are projected to further increase due to climate change. While some of the drivers of drought risk are well known for some systems and regions, drought risks and impacts remain hard to assess and quantify.

The European Drought Risk Atlas is a considerable step towards impact-based drought assessment and can support the development and implementation of drought management and adaptation policies and actions. It characterises how drought hazard, exposure and vulnerability interact and affect different but interconnected systems: agriculture, public water supply, energy, river transportation, freshwater and terrestrial ecosystems.

The atlas presents both a conceptual and quantitative approach to drought risk for these systems. The conceptual drought risk models (impact chains) are the result of a review of the literature in Europe and consultations with experts to construct visualisations of the most relevant drivers and how they interact to determine risk and impacts. The quantitative estimate of drought risk, based on machine learning techniques, maps drought risk at national and sub-national level in terms of annual average loss and probable maximum losses at specific return periods, both for current climate conditions, and for projections under different levels of global warming (+1.5 °C, +2 °C, +3 °C).

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Executive summary

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In recent years, droughts have had substantial impacts on nearly all regions of the European Union, affecting several critical systems such as agriculture, water supply, energy, river transport, and ecosystems. These impacts are projected to further increase in the coming decades due to climate change. While some of the drivers of drought risk are well known for some systems and regions in the EU (e.g. drying climate in the Mediterranean), drought risks and impacts remain hard to assess and quantify.

This Drought Risk Atlas is an effort to better understand, estimate and map drought risks in the EU. In particular, it attempts to characterise how drought hazard, exposure and vulnerability drivers interact and affect different systems, notably: **agriculture**, **public water supply**, **energy**, **river transportation** and **terrestrial** and **freshwater ecosystems**. Next to presenting hotspots of drought risk for these different systems under current climate conditions, this Drought Risk Atlas also provides insights into how risks may change in relation to different projected climate conditions.

The findings presented in this Drought Risk Atlas are the product of a combination of research methods: an in-depth review of the literature on drought risks in Europe, consultations with experts to construct conceptual models of drought risks (impact chains), and the application of a quantitative drought risk assessment methodology based on machine-learning. The conceptual risk models used in the Drought Risk Atlas aim to visualise the most relevant drivers influencing hazard, exposure and vulnerability, and how these interact to determine risk and impacts. The quantitative impact analysis, based on machine learning techniques, maps drought risk at the subnational level in terms of average annual loss and probable maximum losses at specific return periods, both for current climate conditions and for projections under different levels of global warming (+1.5 °C, +2 °C, +3 °C compared to the pre-industrial period).

Drought impact estimates for **agriculture** under current climate conditions show that reductions in crop yield may be substantial. Average annual reductions in yield are estimated as up to 10% less than the expected amounts, with the highest risks located in the Mediterranean area (in Spain the average annual yield reduction is over 5% for wheat and exceeds 10% for barley) and Romania. These reductions are driven by different crop-dependent factors. For rain-fed crops (e.g. wheat), drought indices linked to precipitation (atmospheric water supply) and precipitation minus evapotranspiration (water balance) are the best predictors of drought impacts. However, the impact chains show that the risk of adverse consequences for agriculture is also driven by several vulnerability factors such as soil conditions and agro-management practices. In the long-term intensive tillage, for instance, can result in thinned or compacted soils that have reduced water storage capacity, thus contributing to crop water stress. Consequently, soil and water conservation practices may contribute to drought risk reduction and adaptation. Projections for agricultural drought risk in Europe under climate change generally follow the north-south gradient of overall mean drying (south) and wetting (north). Wheat and barley production is expected to decrease in southern and western Europe, with Spain suffering worse impacts also due to high exposure.

For **irrigated agriculture**, some practices can contribute to effective adaptation. For instance, more efficient conveyance of water has the potential to decrease water use. However, great care should be taken, and it needs to be accompanied with appropriate policies to avoid a rebound effect (e.g. an increase in water extraction driven by greater irrigation efficiency). Action on pricing schemes that encourage water conservation (i.e. volumetric pricing) can also help decreasing risk. Another element driving the availability water was found to be the level of diversification in water resources used for irrigation. In this regard, policies such as the EU Water Reuse Regulation can increase diversification, whilst accounting for potential negative effects downstream. Given that irrigation practices and choices both depend on a variety of factors and may change over time some complex irrigated systems, such as rice cultivation, have here been excluded from the analysis of projected climate conditions.

For **public water supply**, impacts are driven by a variety of factors. Besides water quantity, water quality is also important for water supply. Deterioration of water quality, resulting from an increased concentration of pollutants due to lower water levels, may require enhanced water treatment and increased quality monitoring capacities in order to adhere to the water quality standards defined by the European Water Framework Directive, therefore with associated costs. Entry points for adaptation thus revolve around both water quality and quantity, making the recast of the EU Drinking Water Directive an important tool. The relationship between drought and water abstractions is complex, as the latter can be a short-term solution to as well as a driver of water shortage across systems. Moreover, the dynamic relationship between drought conditions, demand and abstractions for public water supply makes it harder to extrapolate a correlation between hazard indicators and impact for this system. Last, various price effects are forecast to come into play as additional treatment may be required and limited water supplies might increase prices. As such, the effects of droughts on public water supply are difficult to simulate. Nevertheless, the quantitative risk analysis reveals that the highest average annual increase in drought-induced water abstraction is currently estimated for Spain, France and Romania. Under projected climate conditions, drought-induced water abstraction is expected to increase around the Mediterranean, especially at global warming levels of +2 °C, and +3 °C.

For the **energy** system, the currently active hydropower and nuclear power plants are affected by droughts, through lower reservoir or river levels and through restrictions on cooling water use respectively. In relative terms, drought-induced losses in nuclear power generation are generally smaller (average annual loss of about 1%) than hydropower losses (average annual loss up of to 10% in southern Europe). These losses are driven by all types of hydro-meteorological deficits (quantified by using precipitation, evaporation, and discharge-based drought indices). While these hydro-meteorological drivers are significant, the impact chains also highlight the importance of factors like reservoir management for hydropower and plant cooling technologies for thermoelectric energy (such as nuclear power) in determining drought risk. These are entry points for adaptation, since dry or hybrid cooling would reduce the vulnerability of thermoelectric systems to drought. Projections of risk under climate change (not accounting for a change in the number of power plants) for hydropower follow the gradient of average drying in the south (with considerable rise in drought risk in Portugal, Spain, Italy and Greece) and wetting in the north-east of Europe. Instead, for nuclear power, greater variability in precipitation and higher potential evaporation driven by increased warming, seem to increase risk in the whole of Europe.

In the case of **river transportation**, the average annual loss in transported goods generally stands at below 2.5% across Europe. Short-term discharge-related drought indices are key predictors of disruption of the quantity of goods transported on waterways. However, the impact of disrupting economic activity can be mitigated by addressing various vulnerability drivers as identified in the impact chain, for instance the composition of the shipping fleet (e.g. vessels adapted to low flow conditions). Moreover, in river transport the interconnectedness between systems and cascading impacts are important factors. For example, reductions in river transport may affect the transportation of fuels to thermoelectric power plants, impacting energy supply. Therefore, managing supply and increasing stock capacities may be important drought adaptation factors to be considered by companies depending on inland water transport. Future projections indicate relatively small changes in risk under climate change, although average wetting and increased melt in large river basins may have a positive effect (e.g. in the Rhine), whereas greater variability may increase the risk upstream or in smaller river systems (e.g. in the upper Danube).

Average annual drought losses in net primary production for both forest and freshwater **ecosystems** reach up to 4%, particularly in the north and east of Europe. Projections of drought impacts under climate change follow the south (dryer, more impacts) to north-east (wetter, fewer impacts) gradient visible with increasing global warming. For forests, however, reductions in risk are apparent only in the far north and greater risk is projected in central and southern Europe, particularly around the Mediterranean. Deficits in precipitation and precipitation minus evapotranspiration are important drivers affecting net primary production through regulation of water (un) availability. Nonetheless, the impact chains illustrate that in the case of **forest** ecosystems, there are also multiple forest management practices that can affect the resilience to drought. For instance, in managed forests, shorter rotation cycles decrease the time trees are exposed to potential drought events. Moreover, appropriate mixing of tree species (for both production and natural forests) increases the likelihood that diverse physiological characteristics might have complementary effects and be able to reduce drought impacts. When it comes to **freshwater** ecosystems, their water requirements in terms of quantity, quality and timeliness (i.e. their “environmental flow”) make them particularly vulnerable to changes occurring in these parameters due to competition for water resources with other sectors. Prolonged or profound changes can immediately affect both animal and plant communities, triggering an ecosystem shift from which recovery may be difficult. Here the interconnectedness between systems is once again very evident, as many drivers are related to demands in other systems, such as electricity generation and river navigability. In addition, increased soil erosion in agricultural watersheds is a major contributor to the contamination of water bodies. Establishing buffer zones around the designated ecosystems provides an entry point for adaptation.

Looking at drought risk in the various EU regions with a multi-sectoral perspective, **southern Europe** (Mediterranean area) has the highest drought risks in the systems considered. Moreover, this region is set to have the largest increases in risk due to climate change (driven by a general drying). Within this region, the Iberian Peninsula is most at drought risk under both current and projected climate conditions. In **northern Europe** (Scandinavia and the Baltic area), projections show less change in drought risk between current and projected conditions (if compared to those for southern Europe), with different and less clear signals. For some systems (e.g. agriculture, hydropower), a slight decrease in the average drought risk for this area (particularly the Baltic area) due to climate change is expected, since conditions that are on average wetter are projected. However, substantial risks of drought impacts remain as precipitation variability is forecast to increase everywhere, together with the frequency and the intensity of extreme drought events (even if conditions become wetter on average). **Eastern and western Europe** may experience more complex effects and impacts. Some projections show increasing drought risks, while others show similar or even decreasing risk, owing to the interplay of drying/wetting dynamics and greater variability in precipitation. Notably, Romania already often has relatively high risks, and projections show an increase in risk (e.g. for agriculture, water supply, hydropower production, terrestrial and freshwater ecosystems). France is a transition country, where the higher risk of the south can be also found in the north with rising warming levels (for agriculture, water supply, terrestrial and freshwater ecosystems). France is also a hotspot for losses in both nuclear and hydropower, which are projected to significantly increase in climate projections especially for hydropower.

The **limitations** of this Drought Risk Atlas are acknowledged, in particular those related to future projections, which are based on climate simulations (hazard), without taking into account any other future change in exposure or vulnerability. Future socio-economic development that may lead to technological improvement, effects of rising atmospheric CO_2 concentration on vegetation and crops (CO_2 fertilisation), changes in exposure and resource management have not been considered. Uncertainties in the future climate projections may also affect the main outcomes. For instance, snowpacks at high altitude or latitude may at first contribute to more water resources but may collapse when complete melting nears. Moreover, drought impact data are sometimes sparse and fragmented which can increase result uncertainty. Therefore, systematic monitoring and collection of quantitative data on drought impacts (at a pan-European scale) is highly recommended.

With its overview of EU drought risks under the current and future climates, the Drought Risk Atlas can support the development and implementation of drought management policies and inform adaptation actions. The methodologies of the impact chains and quantitative risk estimations developed for this Drought Risk Atlas can be transferred to other scales (e.g. Member States, river basins), to allow the use of more detailed information and high-quality data and to enable the targeting of specific systems and impacts that are particularly relevant for the respective contexts. The impact chain methodology stands as a first step towards impact-based forecasting and advancement from the drought hazard forecasting that is currently the standard practice.

Overall, whilst this Drought Risk Atlas has evaluated risk per system, a systemic cross-sectoral approach to drought risk management is recommended, urging EU policymakers to consider interconnections and cascading risks between systems. This holistic approach, ideally integrated with compound risks, cascading effects and other aspects of water management such as flood management, would support a proactive approach to managing current risks, ensure resilience in the face of anthropogenic climate change, and prevent unintended consequences of maladaptation.

CHAPTER 1

Introduction

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In times of drought, our essential yet fragile connection with water which we often take for granted comes into focus, from as personal a relationship as drinking, cooking or washing, to production of our food, to goods and services produced close by or far away, and to the good health of the ecosystems we depend on and want to conserve. A prolonged lack of water endangers lives, livelihoods, and the balance of our social-ecological systems and leaves nothing and no one unaffected. The European Union is not immune to these risks, as the highly impactful droughts of 2018, 2022 and 2023 have shown (see box “Drought in the European Union”).

To be better prepared to reduce, manage and adapt to growing risks and impacts deriving from droughts, it is paramount to understand and assess drought risks in a comprehensive manner, mindful of the diverse impacts they can entail for different, often interdependent, economic sectors and systems. In particular, identifying common challenges and the drivers behind these can lead to finding solutions that can address drought risks across sectors and systems. A cross-sectoral approach to address drought risks also helps to minimise the chances of negative trade-offs over increasingly scarce water resources in a future influenced by increased water demand and affected by climate change.

Recognising the importance of better understanding current and future drought risks for Europe, the European Drought Observatory for Resilience and Adaptation (EDORA) project has developed an innovative approach to analyse drought risks for different sectors and systems in the European Union. Five sectors and systems of interest have been considered: agricultural crop systems (rain-fed and irrigated), public water supply, energy production, river transportation, and ecosystems (terrestrial and freshwater). Drought risks for these sectors and systems were assessed drawing on an approach that integrates findings from the literature, expert consultations, and a data-driven assessment for the 27 member countries of the European Union (EU27) under both current conditions and projected climate scenarios. By presenting the main results of this work, the European Drought Risk Atlas, offers for the first time, a detailed and disaggregated view on the risks that droughts inflict on socio-economic sectors and ecosystems along with their underlying risk drivers – an essential step in improving our preparedness and in increasing our resilience to recurring droughts. This atlas does not claim to cover the complete range of drought impacts on society and the environment, as not all indirect or even direct impacts of droughts can be accounted for precisely, given that some impacts remain little documented and even less quantified. Nonetheless, this atlas does present for the first time a broad cross-regional and systemic picture of drought risks in Europe.

1.1 Drought impacts and risk

1.1.1 What is a drought?

The Sixth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC) defines drought as "*an exceptional period of water shortage for existing ecosystems and the human population (due to low rainfall, high temperature and/or wind)*" (IPCC 2022). This definition stresses the importance of the temporary nature of the water deficit distinguishing droughts from long-term conditions such as water scarcity and aridity (Van Loon et al. 2016; UNDRR 2021). Therefore, in this atlas, drought hazards are identified as prolonged periods of "less water than normal", i.e. compared to the historical reference period (1981-2020). Another important component in the IPCC definition is the identification of *what* is at risk of drought, i.e. "ecosystems and the human population". While the IPCC definition is apparently generic, this formulation actually encompasses the great diversity and complexity of possible drought impacts, and consequently implies the necessity of tying the definition of drought to the specific impacts it can have.

However, because of these characteristics, droughts remain difficult to define conclusively (Slette et al. 2019), and which types of drought are being investigated is often not specified in the research literature (Hagenlocher et al. 2019). The customary characterisation of droughts by Wilhite and Glantz (1985), which distinguishes between meteorological (i.e. related to precipitation deficit), agricultural (i.e. related to soil moisture deficit), hydrological (i.e. related to water stored in rivers, lakes, groundwater and artificial reservoirs) and socio-economic drought (i.e. associated with impacts of the three above mentioned types on wider society), has recently been reconceptualised as different manifestations of the same drought event rather than separate typologies (UNDRR 2021). An important evolution in our understanding of droughts is the recognition that, far from being exclusively natural phenomena, they are complex socio-natural events, driven by natural (e.g. lack of precipitation) and human processes (e.g. water abstractions, land use changes, Van Loon et al. 2016). In fact, it is the interaction between drivers such as natural variability, micro-climate conditions, water demand and uses, human-induced climate change and water management responses, that triggers many droughts and their potential impacts, suggesting that they ought to be thought of as anthropogenic in nature (AghaKouchak et al. 2021).

1.1.2 Drought impacts

Droughts can have long-lasting direct, indirect, compound and cascading impacts across economic sectors, systems, borders, and regions (UNDRR 2021; Hagenlocher et al. 2023). Given the number of systems potentially affected (e.g. agriculture, industry, public water supply, ecosystems) and their specific interactions with water resources, the impacts connected to drought are extremely multi-faceted. In agriculture, a temporary water shortage can be very detrimental depending on the phenological stage during which it occurs, leading to significant losses in crop yield. However, this impact can already widely differ in terms of the crops involved (each having different water requirements) and, even more importantly, given the presence or absence of irrigation, which in turn can constitute a driver for water shortages in itself when its use is not managed sustainably. In other systems, the impact of drought can manifest in even more complex pathways. Ecosystems, for example, when confronted with prolonged water shortages, can undergo dynamic changes in terms of composition, structure, and functions, leading to a loss of ecosystem services and, when ecological tipping points are surpassed, to full regime shifts (Grizzetti et al. 2017), i.e. transition to a different ecological state, a condition from which recovery becomes more difficult. Impacts from drought can also affect activities such as industrial production and transportation, and create challenges for the provision of public water supply.

Drought impacts can themselves be evaluated using different lenses. One way is to look at them as harmful effects cascading through social-ecological systems, categorising them in terms of direct or indirect impacts: the former can be understood as issues immediately emerging from the water deficit in the system (e.g. losses in crop yield), while the latter refers to secondary consequences derived from the direct impacts through the interdependencies of our economic sectors and systems in our highly interconnected world (e.g. loss of employment, price rises or an increase in conflicts between users) and through social consequences and harmful coping mechanisms (e.g. reduced mental health) (UNDRR 2021). Additionally, drought impacts can manifest with considerable delay and, through teleconnections, negatively affect areas that are far away from where the drought occurred (Wens et al. 2019; Hagenlocher et al. 2023). Another lens for evaluating drought impacts is the assessment of their financial costs. Such quantification requires estimates of observed damages and losses. However, the indirect impacts, which could substantially swell the final estimates, are not fully tracked, and considered in many cases (UNDRR 2021), and quantitatively attributing these to droughts remains difficult. An example of this incomplete accounting is the loss in the value provided by ecosystem services (deriving for instance from biodiversity loss, ecosystem degradation or stress), which is seldom accounted for in monetary terms in loss estimates and is often a compound result from several degradation processes that interact with a drought.

1.1.3 **Drought risks**

Understanding what the drought risks that our societies and life supporting systems are subject to is important in reducing, managing and adapting to the impact of future events. For this purpose, knowing which drought impacts have affected our society and ecosystems in the past gives us the opportunity to investigate the risks of these impacts manifesting again in the near and distant future. Risk assessment can use impact information not only to find out which drivers contribute to a specific type of drought risk and how they interact, but also to provide a quantitative estimate of the current levels of risk for different sectors and systems.

In order to meaningfully assess drought risks, it is essential to break down their complexity into main components, which can then be analysed. Achieving this requires a conceptual framework of risk that can provide theoretical guidance. The IPCC AR5 framework (IPCC 2014) formalised the notion that risk is a product of three separate components: hazard, exposure, and vulnerability. This framework has greatly influenced the conceptualisation of risk across disciplines and has spurred countless applications to all sorts of risk. Nevertheless, the complex characteristics of drought risks make it necessary to expand this framework to capture the systemic nature of drought risks. Figure 1 shows a novel systemic framework developed by Hagenlocher et al. (2023) to inform drought risk research and policy.

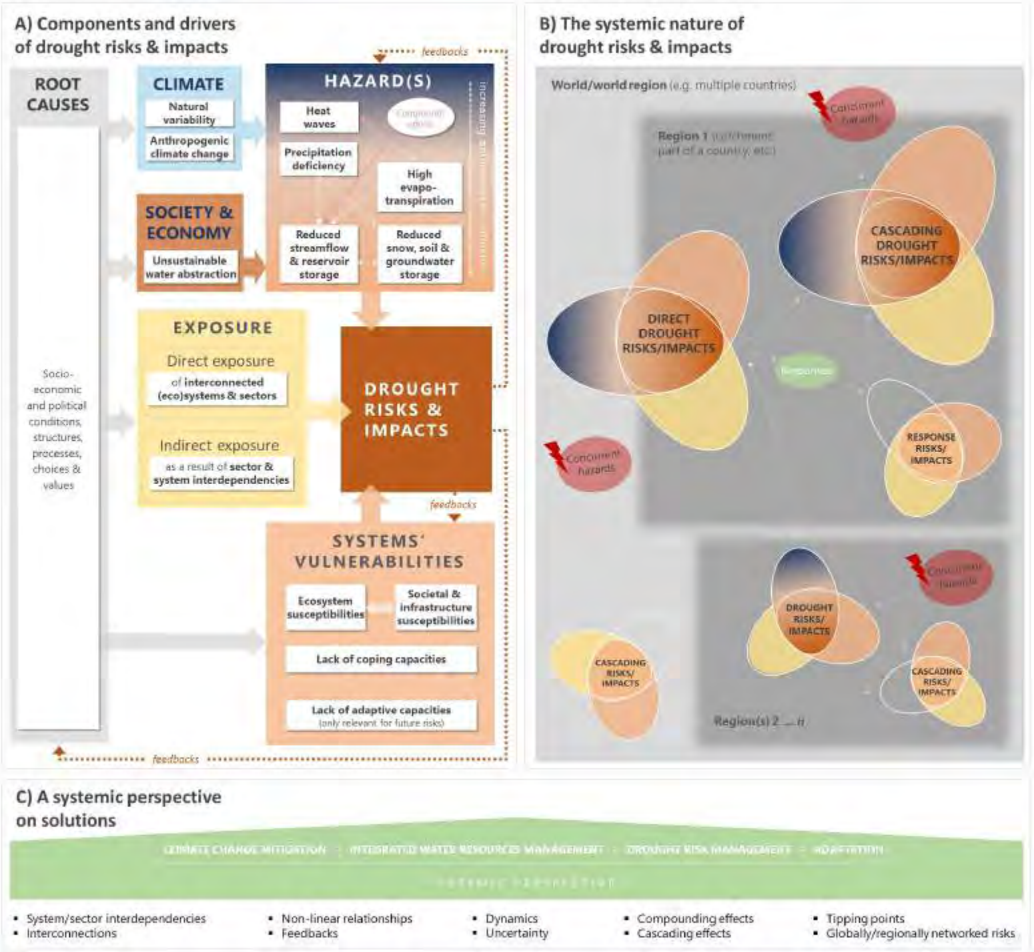

Figure 1: The systemic nature of drought risks and impacts (Hagenlocher et al. 2023).

The framework combines guidance on the specific characteristics of hazards, exposure, and vulnerability in the case of drought risks (including their dependency and feedbacks on root causes that affect societal and environmental processes alike; Panel A of Figure 1), with a representation of how drought risks and impacts can cascade and compound with other hazards across scales and systems, highlighting the role of responses (Panel B, Figure 1). Moreover, it highlights the important role of systemic solutions to effectively tackle drought risks (Panel C, Figure 1).

Following Panel A (Figure 1), we can explain the role of all factors conducive to drought risks and impacts and use this to inform our risk assessment (see Section 1.2 for specific details on the EDORA approach).

The hazard component of drought risks refers to the drivers and conditions that bring about the water shortages and affect our systems. When considering drought hazard, its drivers do not only relate to a shortfall of precipitation (including snow) over a certain period, but also extend to the negative water balance as a consequence of increased evaporation due to high temperatures (e.g. during heatwaves) or strong winds. However, the occurrence of water shortages is also extremely dependent on human activities. For instance, an increase in overall water abstractions to satisfy high water demand can exacerbate precipitation-related shortages. Similarly, while temporary mitigation measures can alleviate present impacts, they can also affect future availability. One such example is groundwater pumping for irrigation: while it can safeguard agricultural production in a year affected by water deficit, it will also inevitably contribute to further depletion of the groundwater table, thus reducing future mitigation options and ultimately increasing risk for multiple sectors and systems. An additional challenge is determining the actual beginning and end of a drought. Typically, droughts have a slow onset and an indeterminate end. This means that pinpointing of their conclusion is dependent on what indicator and reference period are chosen, and no universal metric is available. Moreover, in terms of duration, drought can last from a few weeks to multiple years or even decades (megadroughts).

The second component of drought risk is exposure, which in general indicates "*the presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected*" (IPCC 2023). In the case of drought, this apparently straightforward concept can unfold in more complex forms. When considering people, for instance, their exposure to drought is in general not direct (i.e. affecting them physically), but rather mediated through impacts on systems they depend on (e.g. food production and public water supply). This is also the case of low-flow events, which directly affect navigability for an entire river system for the former, and the position of industrial plants on specific points of the same river for the latter. This indirect exposure is the result of many interdependencies between our sectors and systems.

Lastly, all systems exposed to drought, whether directly or indirectly, will suffer adverse consequences in relation to their vulnerabilities: these encompass ecosystem susceptibilities (e.g. the characteristics of soils and vegetation), as well as, societal and infrastructural ones (e.g. activities or sectors strongly dependent on only one source of water, unstable food markets etc.) together with coping capacity (such as the availability of insurances against losses, the presence of drought risk management plans, or the state of existing reservoirs). In addition, the impacts experienced in systems are also influenced by the coping and adaptive capacities of these systems.

It becomes apparent from this overview that when confronted with droughts, we are not looking at a single, generic drought "risk", but rather a multitude of drought risks for different sectors and systems, each with its defining features, depending on the system considered. Consequently, when assessing drought risks, the choice of hazard indices must be adapted to each impact of interest, while sector/system-specific drivers of exposure and vulnerability need to be understood and included. Moreover, it is essential to obtain a clear representation of the causal relationships, contributing factors, and feedback loops of all these elements. Also synergies and trade-offs in risks between the sectors and systems evaluated, which are intrinsically linked within society, should be considered. The development of approaches to assess and manage the cascading and systemic nature of drought risks (represented in the Panels B and C of Figure 1) is still nascent, and further research is needed to develop guidelines and tools in this sense (see box: "Outlook on drought research: the need for a systemic perspective").

1.2 **EDORA approach to assessing drought risks**

The EDORA approach to drought risks assessment, presented in this atlas, aims to address the complex characteristics of drought hazards, drought risks and impacts, as outlined above. Focusing on the EU27, the approach was developed and implemented to assess drought risks for single sectors and systems, each characterised by its own underlying exposure and vulnerability drivers. The analysis builds on two major complementary components (Figure 2): the construction of sector/system-specific conceptual models of drought risk (also known as “impact chains”) and the quantitative data-driven assessment of sectoral drought risk based on machine learning models and the available data. Impact chains offer a visual representation of how drivers of risk interact to produce a certain drought risk, thus providing a useful guide for the data-driven assessment (see Section 1.3.1), but also entry points for managing the drivers of drought risks. The data-driven approach builds on the impact chains by estimating the risk for system-specific direct impacts. Based on the data available, the relationship between drought hazard and impacts indicators is assessed, while also considering exposure and vulnerability indicators (see Section 1.3.2). This approach complements the impact chain-based one by offering insights into spatial hotspots and temporal dynamics of drought risks in the EU, while not claiming to quantify the whole impact chain. The analysis was performed for the EU27 territory, at multiple spatial scales (based on data availability for each sector or system). The following sections give an overview of the methodology implemented for both components. A more detailed descriptions can be found in Annex I.

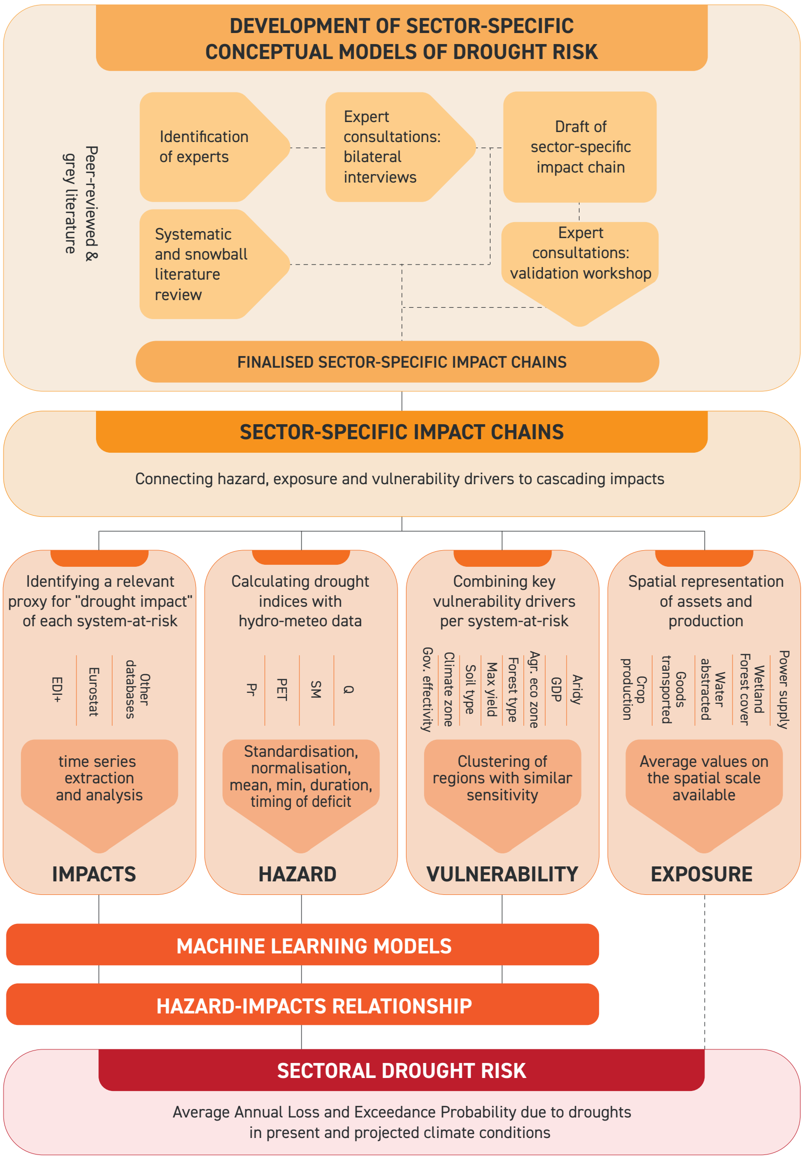

Figure 2:
EDORA approach to drought risk assessment.

1.2.1 **Conceptual models of sector-specific drought risks: EDORA impact chains**

The conceptualisation of drought risks in the EDORA project builds on the impact chain methodology (Fritsche et al. 2014; Hagenlocher et al. 2018; Zebisch et al. 2021). Impact chains are conceptual risk models which visually represent drivers of risks and their interactions. These can be system/sector-specific characteristics and processes but may also sometimes overlap between systems and sectors. In impact chains, drivers of risk are generally identified and organised according to their relevance for the subcomponents of risks (hazard, exposure, vulnerability), while an “intermediate impacts” space is added to facilitate the explanation of the interactions between drivers.

The EDORA impact chains were built through an iterative process of literature review and expert consultations and validation, to achieve comprehensive and concise representation of drought risks for different sectors and systems and their underlying risk drivers. An important first step in the analysis was pinpointing the main risks of interest in each sector since multiple possible impacts are identifiable in each of them. An overview of the selected risks and impacts is shown in Table 1.

Subsequently, drivers of risks were identified by analysing and synthesising the inputs obtained from the consulted experts and the information present in the literature; these were then categorised as either climate signals, hazard, exposed element, vulnerability driver or intermediate impact, and their interlinkages represented in a visual model. The resulting conceptual models are presented and explained in the following sections. The models were discussed and validated through a series of workshops with sector experts (see Annex I).

1.2.2 Data-driven approach to risk estimation

The data-driven approach implements an impact-centric approach that relates information on various drought impacts with hazard drivers. Using the information retrieved by the impact chains, best proxies of impacts, vulnerability factors and exposure were identified at the pan-European level. European regions are clustered based on their vulnerability to drought risks, under the assumption that the hazard-impact cause-consequence relationship is similar within one cluster of regions with similar vulnerability, while differing from regions in other clusters. Machine learning (ML) models are subsequently trained to learn the relationship between impact and drought hazard per vulnerability cluster and this relationship was used to estimate the risk (in terms of likelihood of experiencing certain impacts). This was summarised into the average annual loss risk metric, indicating the estimated average annual drought-induced impact. This metric is expressed in relative production loss (% of region-specific production) and can be combined with exposure data to estimate average annual and probable maximum production losses. As such, an impact-based drought characterisation is performed, enabling creation of a region- and sector-specific definition of impactful droughts and estimations of drought risk. Being a data-driven approach, the accuracy of estimated risk depends strongly on the quality of the impact and hazard information available (data sources *per* system are described in Annex II).

Sectors and systems

The EDORA project addresses a diverse spectrum of systems relevant for the EU context. Systems and related risks and impacts are reported in Table 1.

System	Attribute or subsystem investigated	
	by impact chains	by data-driven method
Agriculture	Crop yield (irrigated and rain fed separately)	Crop yield (irrigated and rain fed jointly)
Water supply	Unmet household-consumption water demand	Water abstraction for public water supply
Energy	Unmet energy demand by consumers	Hydro and nuclear power production
River transportation	Disruption of industrial and coal-based energy production	Inland transportation of goods
Terrestrial ecosystems	Decreased forest health	Anomaly in net primary production
Freshwater ecosystems	Disruption of environmental water flow necessary to maintain the ecosystem functions	Anomaly in net primary production

Table 1: Key systems and drought-exposed attributes analysed in the EDORA project.

Estimation of risks in projected climate conditions

When evaluating future risks by using climatic projections, the hazard-impact relationship is recalibrated using indices that can be derived from historical climate model runs, and then applied on future model projections to derive how drought risks may change in future climates while keeping exposure and vulnerability constant. For this purpose, we used an ensemble of Regional Climate Models (RCMs) from the EURO-CORDEX (Jacob et al. 2014) initiative (11 models) under two Representative Concentration Pathway (RCP) scenarios RCP 4.5 and RCP 8.5. Three global warming levels (GWLs; +1.5 °C, +2.0 °C, +3.0 °C) above those of the pre-industrial era were considered. By pulling together impacts data from different regions into the same clusters, we used space-for-time substitution to increase the sample of observed events to train the model. Nonetheless, the method cannot estimate the impacts of unprecedented events (as there is no historical example for establishing the relationship). In addition, socio-economic evolution and technological development which may lead to relevant changes in exposure (e.g. changing crops, constructing, or decommissioning assets) and vulnerability (e.g. added irrigation capacity), or other effects such as CO_2 fertilisation are not taken into account. Beside this, many of the drought impacts considered here can also have underlying economic impacts through price effects. For instance, market shortage may raise prices in relation to energy or agricultural production. To account for these effects, dedicated economic modelling would be necessary. As such, these results should be regarded as the isolated effect of hydro-meteorological changes and should not be intended as comprehensive risk scenarios for future moments in time.

Drought in the European Union

In the past decades, countries in the European Union have experienced multiple drought events, with severe consequences. Since 2011 alone, the European Drought Observatory (EDO) has reported the occurrence of 21 severe drought events[1]. Of these, the 2022 drought was one of the most devastating (Toreti et al. 2022), with an incomplete recovery from its impacts over the following winter, thus contributing to the drought in early 2023 (Toreti et al. 2023). Importantly, recent drought events have not only touched the historically more affected southern region of the EU, but have expanded to central, eastern and, to a lesser extent, northern Europe (Blauhut et al. 2022; UNDRR 2021), while losses caused by these events extend to multiple sectors of interest (Blauhut et al. 2022; Cammalleri et al. 2020).

Impacts from these events have been registered in sectors and systems as diverse as agriculture and livestock farming, public water supply, forestry, the energy sector, aquaculture, ecosystems, and human and public safety, as reported by the European Drought Impact Report Inventory (EDII) (Blauhut et al. 2022) as well as across sectors and systems in the form of cascading effects (Hagenlocher et al. 2023).

In economic terms, annual losses related to droughts in the European Union and the UK have been estimated to be about €9 billion (Cammalleri et al. 2020), an imposing figure which is however considered an underestimation, as some impacts, such as damage to the environment or to human health, are more difficult to evaluate (Cammalleri et al. 2020; Blauhut et al. 2022).

This has drawn attention to the vulnerability to droughts of the European sectors and systems. In particular, the frequency of these events is shrinking the recovery window between impacts, leading to even more severe consequences. For instance, in early 2023, signs of drought started to emerge due to an exceptionally warm and dry winter, with effects of the 2022 drought event persisting (Toreti et al. 2023). The lack of precipitation and the mild temperatures led to low snow accumulation, which was far below the historical average in the Alps, resulting in negative soil moisture and river flow anomalies (ibidem). This compounded with the depletion of water resources in snowpacks, groundwater and reservoirs that had occurred during the previous year, and which had not yet fully recovered. This factor alone increases drought risks for different sectors, as seen, for instance, in France and Italy for public water supply, agriculture, and energy production (Toreti et al. 2023).

While climate change has already led to more intense and longer meteorological droughts in southern Europe (UNDRR 2021), almost all the EU is expected to be more affected by drought events under increased climate change, with more frequent and/or severe agricultural and ecological droughts projected to occur at 2 °C or above (IPCC 2023). The regions expected to experience the largest drought frequency increase under RCP 4.5 and RCP 8.5 scenarios are southern Europe, and France, while central Europe and southern Scandinavia show a moderate increase in drought frequency (Spinoni et al. 2018). In terms of future severity of drought hazards in the continent, this is projected to strongly increase over southern Europe and over northernmost Scandinavia (Spinoni et al. 2018).

European Union, Copernicus Sentinel-X imagery

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[1] https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1051, last access: June 2023

Outlook on drought research: the need for a systemic perspective

During drought events, the interconnectedness and interdependence of systems and sectors often becomes more evident, as we observe impacts cascading from one system or sector into risks or impacts, and to the next, sometimes affecting locations in distant areas (UNDRR 2021; Hagenlocher et al. 2023). Therefore, drought risks need to be understood as complex, non-linear and often indirect interactions between different systems, occurring at multiple scales. This calls for a "systemic risk" lens for analysing and managing drought risks (Hagenlocher et al. 2023). The recognition that drought risk is in and of itself systemic in nature was brought to the forefront especially with the UNDRR's Global Assessment Report - Special Report on Drought (UNDRR 2021). However, this nascent perspective, while increasingly developed by researchers and adopted by national and international organisations, still lacks a conclusive set of tools for its assessment and its translation into policy responses.

Addressing drought as a systemic risk also forces us to consider other risks (e.g. related to different hazards, compounding or not), that may be shaped by the same underlying root causes and therefore offer a space for finding common solutions. While the EDORA project and this atlas provide relevant information on drought risks for different sectors and systems, an assessment and evaluation of the systemic nature of drought risks for Europe is still lacking and could not be conducted within the framework of the project. As a result, further research is needed to understand how different systems in Europe dynamically interact through different risks and impacts, and what methodological approaches could best capture these systemic dependencies.


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Current and projected risk by system

The drought risk results for the analysed systems (agriculture, water supply, energy, river transportation, terrestrial and freshwater ecosystems) are shown in this section. First, the links between impacts, hazard drivers, exposure and vulnerabilities are demonstrated and visualised using impact chains. The demonstration of each impact chain begins with a brief description of the risk for the respective system, followed by identification of the elements exposed to that risk. Next, the climate signals and hazards contributing to the manifestation of this risk are described. Lastly, the complex web of vulnerability drivers and intermediate impacts that interact to contribute to the risk are explained. This provide a comprehensive understanding of drought risks for different systems, including information on relevant underlying risk drivers and their interactions. Based on the identification of these underlying risk drivers and limited by available open-source impact data and observations, risk calculations were performed. Risk is presented in terms of average annual loss (AAL) as well as Probable Maximum Loss (PML; i.e. the loss corresponding to a specific frequency or return period) per sector for both the current situation, and under projected climate conditions (see box "Projected change in hazard conditions") for three warming levels (+1.5 °C, +2.0 °C, and +3.0 °C compared to pre-industrial conditions). Using these results, we explore what drives certain drought impacts and how their risks may vary in the future under changing climate conditions. Please note that these estimates only cover part of the risk and that the assessments regarding the future only consider the effect of changing frequencies and intensities in the hazard conditions currently leading to drought impacts, without considering possible changes in exposure and vulnerability (see above).

Future change in hazard conditions

Climate models are used to project future conditions of hydro-meteorological variables such as temperature, precipitation, evapotranspiration, soil moisture and discharge. In a warmer climate, it is expected that the hydrological cycle will “intensify”. Projections are made for three different warming levels (+1.5 °C, +2.0 °C, and +3.0 °C compared to pre-industrial conditions) based on 11 models and two RCPs.

In Figure 3, changes in the Standardized Precipitation Evaporation Index (SPEI, Vicente - Serrano 2010) are presented. Since it combines precipitation and evapotranspiration, SPEI can be considered a proxy for soil water availability expressed in terms of (and variations in) standard deviations from normal water availability. The map below shows substantial regional differences in the average change in SPEI relative to the current situation, with a north-south gradient showing a decrease (meaning more drought) around the Mediterranean but an increase in northern Europe (particularly Scandinavia and the Baltic states).

While these average SPEI values illustrate the general trend, it is also important to consider that climate variability is projected to increase in many of the models, indicating that extremes (including dry conditions) may happen more often or be more severe, even when averages change only slightly.
For instance, summer droughts can still become more frequent or severe, even if the overall climate gets somewhat wetter.

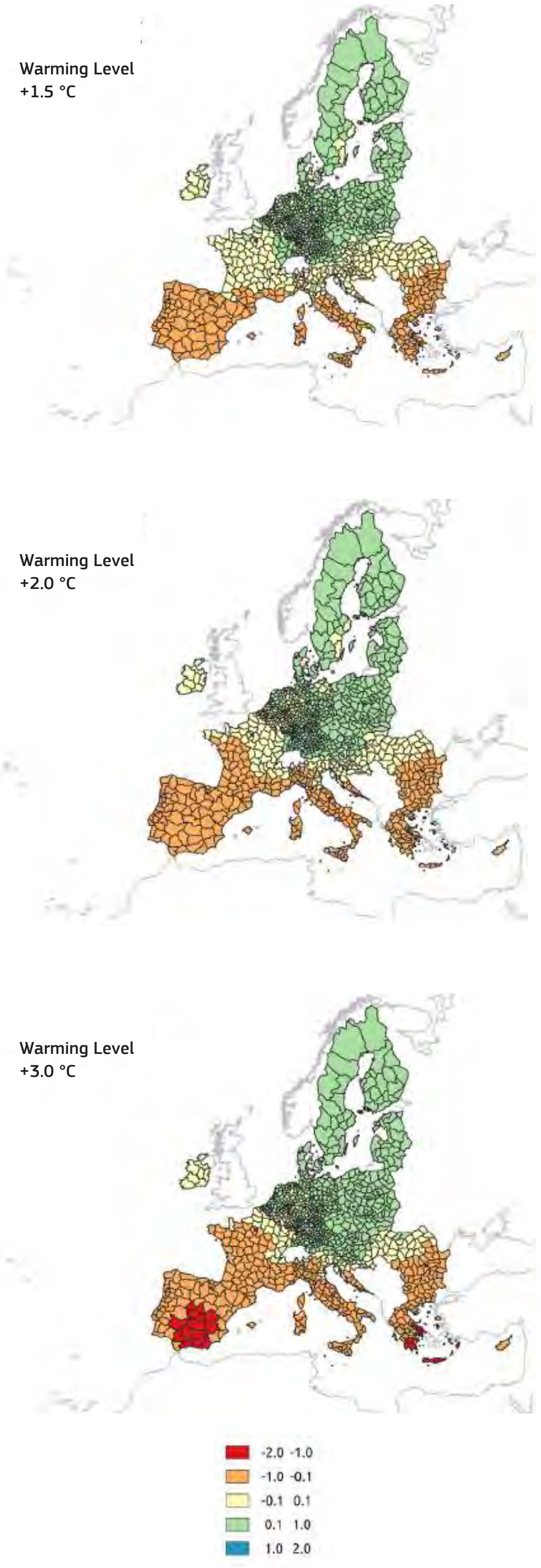

Figure 3:
Average of SPEI-3 values, calculated by averaging standardised 3-monthly precipitation minus evapotranspiration values for each month of the considered period. Averages are shown under different warming levels (WLs), considering RCP 8.5 and RCP 4.5 together. SPEI results are given in units of standard deviation from the long-term mean of the standardised distribution relative to the current conditions. A red area means that the average conditions under the shown warming level equal conditions that are 1 to 2 standard deviations below normal conditions of the current climate, that is, moderate to extreme dry conditions that currently occur only 2.5%-16% of the time will be the “new normal” in that scenario.

CHAPTER 2

Agricultural system

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2.1 **Key facts**

The land used by the agricultural sector in the European Union corresponds to approximately 38% of the region's total land area, distributed across about 10.3 million farms (EC, Eurostat 2021). Most of the land used for agricultural production in the EU (approx. 62%) is arable land producing crops for human and animal consumption. Around one-third is used for permanent grassland, and less than 6% is used for permanent crops such as grapes and olives (ibidem). The share of agricultural land that is irrigated stands at about 6% of the total and is located mainly in southern European countries. Despite occupying only 38% of the area, the agricultural sector accounts for 46% of the total average annual water use, reaching up to 80% in certain regions (ibidem). Around 90% of this amount is used in southern Europe, where irrigation is needed due to the regional climate and type of production type (ibidem). However, irrigation is also used in central and western Europe to improve crop production in dry summers. Overall, agriculture contributes about 1.3% to the European Union's GDP (EC, Eurostat 2021).

Agriculture (crops and livestock) is one of the sectors most affected by drought. Water stress can affect all growth stages of crops and can significantly reduce crop yield (Zampieri et al. 2017). During the 2015 drought, for instance, crop losses of up to 50% occurred in some central and eastern European countries (Van Lanen et al. 2021). In 2022, European crops were again affected by drought, with yield reductions of up to 21% compared to the 5-year average at EU level for some crops (Baruth et al. 2022). Agriculture losses account for more than 50% of total drought losses in Europe, with the highest share in the Mediterranean region (60%, Naumann et al. 2021).

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Impact Chain - Rain-fed agriculture

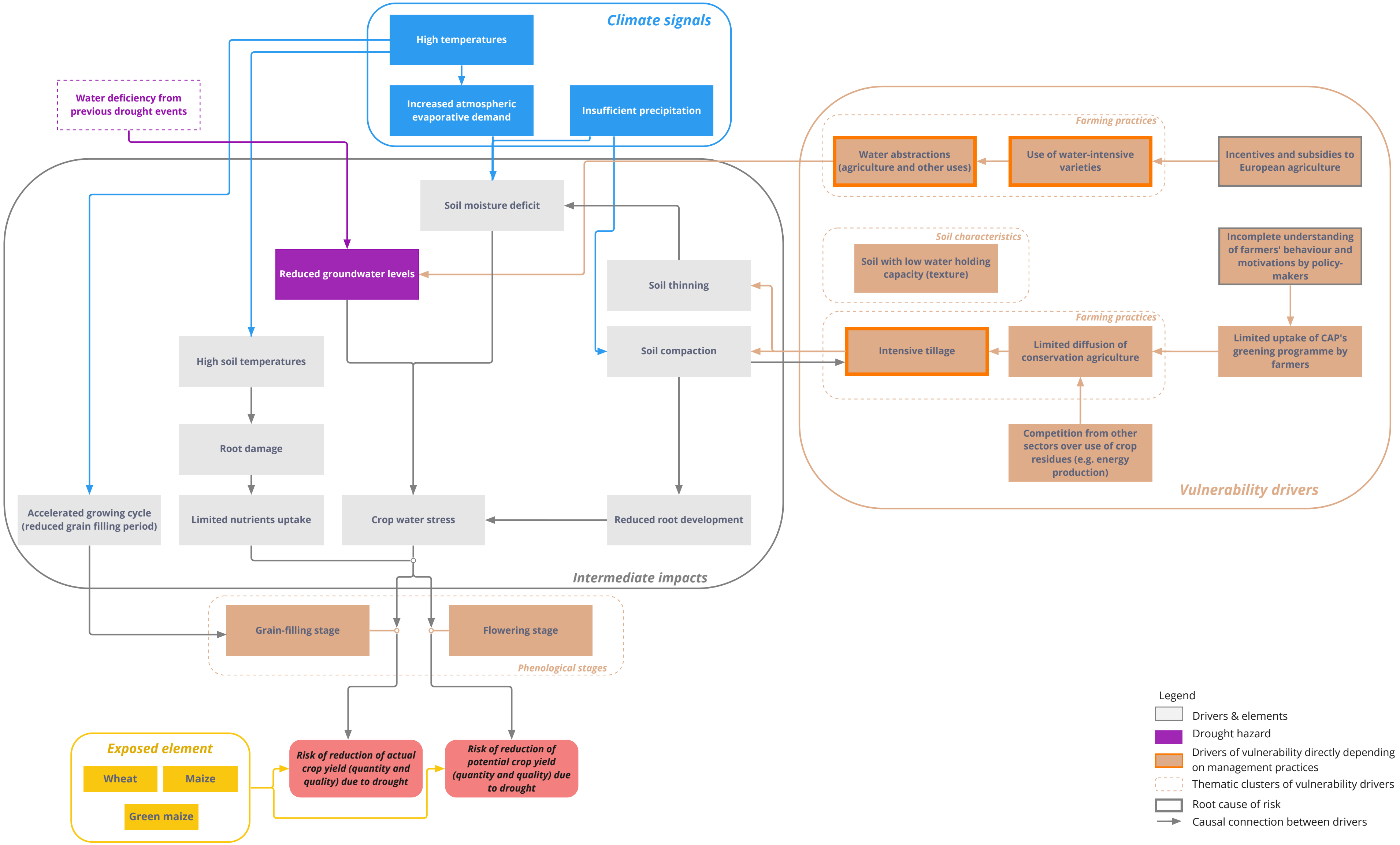

Figure 4: Visual representation of the rain fed agriculture impact chain

Risk (rain-fed agriculture)

The main risk posed by droughts for rain-fed agriculture is a reduction in crop yields. We consider yields both in terms of quantity and quality, this being not only the amount of crops that can be harvested at the end of the agricultural season, but also yield quality (i.e. indicating the qualitative status of the ripened grain).

Exposed elements

Among the commercially relevant crops commonly cultivated in rain-fed systems in Europe are wheat and in some regions maize. Maize is also extensively cultivated in irrigated systems, or under deficit irrigation. However, precise data where and to what extent (deficit) irrigation is used are only recently becoming available (Zajac et al. 2022) and were not included in this study.

Climate signals & Hazard

Rain-fed crops are primarily affected by insufficient precipitation, as it may result in soil moisture deficit (Tramblay et al. 2020), causing water stress for the crops. This deficit can be aggravated by high temperature conditions, due to the resulting increased atmospheric evaporative demand. The accumulated effect from previous drought events can also play an important role. In addition, these two hazard drivers may have a negative effect on groundwater levels, reducing the availability of water that might reach the crop rooting system.

Vulnerability drivers & Intermediate impacts

Prolonged crop water stress caused by a soil moisture deficit and reduced groundwater levels (also aggravated by abstractions) can severely affect the chances of reaching full maturity for the plants. Furthermore, the risk to rain-fed crop yields is also exacerbated in case of high soil temperatures, which can damage the root system, thus limiting the nutrient uptake capacity of the plant (Daryanto et al. 2017). Temperatures can also influence the phenological stages of the crops, for instance by accelerating the growth cycle and thus reducing the grain-filling period. Phenological stages are an important element in the vulnerability of rain-fed crops to drought: the grain-filling and flowering stages are the most sensitive periods for determining the crop yield (quantity and quality) and each crop has different levels of vulnerability during the various phenological stages (Daryanto et al. 2017).

Another element contributing to vulnerability is soil having low water holding capacity (Daryanto et al. 2017). Some farming practices also play an important role in determining crop water stress. For instance, the cultivation of water-intensive crop varieties can increase abstractions and therefore cause overuse of water resources at the basin level (EEA 2009). In the past, European agricultural incentives and subsidies promoted the shift to more water-intensive crops, but more recent EU agricultural policies have moved away from this (EEA 2009). Increased vulnerability to drought can also be linked to farmers' preference for intensive farming practices. For instance, intensive tillage can result in increased tillage erosion (Keller et al. 2019), therefore exacerbating soil thinning (Quinton et al. 2022), which reduces the soil water holding capacity (Kertész and Madarász 2014; Brown et al. 2021; Ranaivoson et al. 2017). Soil moisture retention can be enhanced by conservation agricultural practices, such as the management of crop residues to minimise moisture loss and soil erosion (Ranaivoson et al. 2017). However, this practice is at least partially challenged in Europe by the competition from other sectors for agricultural by-products (e.g. bio-energy production; Rinaldi et al. 2022).

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Impact Chain - Irrigated agriculture

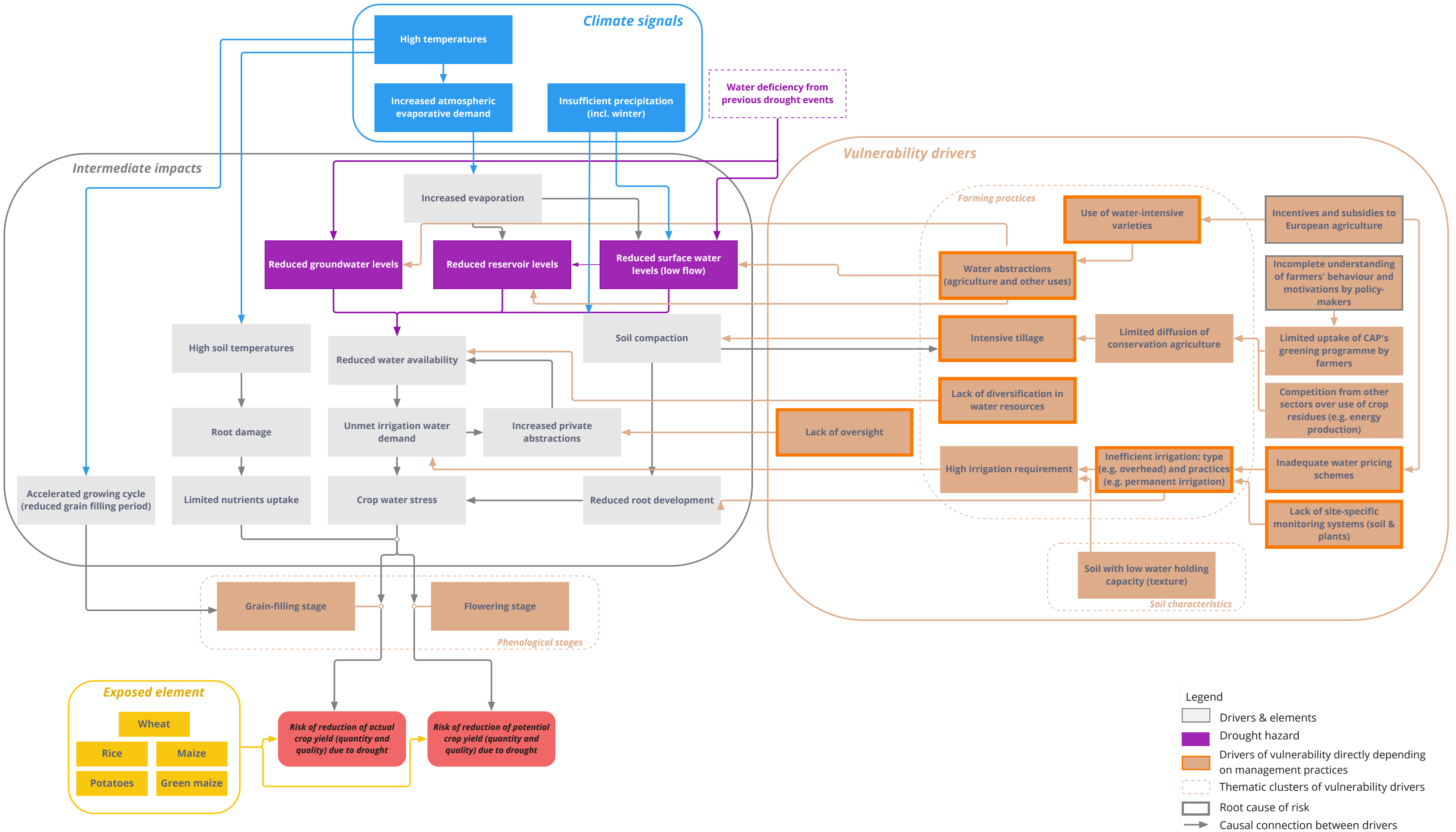

Figure 5: Visual representation of the irrigated agriculture impact chain

Risk (Irrigated agriculture)

Irrigated agriculture is also at risk of a reduction in crop yields, both in terms of yield quantity and quality.

Exposed elements

Irrigation is generally used in Europe used to produce crops with high added value, such as rice. In addition, maize is also extensively irrigated.

Climate signals & Hazards

While some of the climate signals for irrigated agriculture are the same as for rain-fed systems, important differences should be considered. For this system, insufficient precipitation becomes relevant also outside the growing season: insufficient winter precipitation can result in a reduction in surface water levels and, consequentially, reservoirs levels, both of which are water sources for agricultural irrigation. Since in some cases of irrigation water source is groundwater, a reduction in groundwater levels may also be considered a hazard for this system. All these elements are exacerbated by water deficiency from previous drought events.

Vulnerability drivers & Intermediate impacts

Competition for water resources between agriculture and other uses can aggravate the reduction in water levels. Reduced water availability can increase the chances of unmet irrigation water demand, which may lead to crop water stress. In terms of plant-soil-water interactions, irrigated systems suffer from vulnerability drivers and relationships that are similar to those affecting rain-fed systems. However, additional elements play a role because of irrigation needs. In particular, a reduction in water availability can be intensified by a lack of diversity in water resources (Rey et al. 2017; Mereu et al. 2016). The vulnerability of this system is also increased by the high irrigation requirement necessary for yield outputs targets: this can be exacerbated by physical conditions, such as soil with low water holding capacity, but is also a function of low-efficiency irrigation and practices that are not geared towards water saving (EEA 2009). One reason behind the use of inefficient irrigation resides in inadequate/absent water pricing schemes that have historically been applied in many European countries (Berbel et al. 2019). These have the aim of increasing productivity and revenues for the national agricultural sector, but scarcely reflect the true environmental costs of the depletion of water resources (EEA 2009). A recent policy effort addressing this issue is the new regulation on minimum requirements for water reuse (European Commission 2022), which encourages the use of treated urban wastewater for irrigation purposes by harmonising minimum water quality requirements. However, it should be noted that even in the case of appropriate legislation and guidelines, enforcement is generally limited due to the diffuse nature of the abstraction points, which indicates a lack of oversight (De Stefano & Lopez-Gunn 2012; Alcon et al. 2014). Lastly, poor adoption of technological improvements is an important factor in the vulnerability of this system: the limited use of site-specific monitoring systems for soil and plants particularly restricts opportunities to practise irrigated agriculture while safeguarding water resources (Monaghan et al. 2013).

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2.3 **Data-driven model results**

2.3.1 **Identification of available impact**

Data on crop yields, identified by the impact chains as the main variable impacted by drought, were collected from the Eurostat - Statistical Office of the European Union (1975-2021) and from the JRC Agri4Cast database (1981-2019), see Annex II – Agricultural System for a detailed description. Rainfed and irrigated crops were analysed jointly in this section, as detailed data about irrigated versus rain-fed production are not available. Deficit irrigation is a management decision driven often by the conditions at the specific place and time, and as such is considered part of the risk dynamic. In particular, the analysis was conducted at NUTS-2 administrative level for five crops: wheat (total of soft and durum), maize, barley, potato, and rice. Rice is always irrigated, maize is extensively irrigated, while some of the other crops (potato and barley) are sometimes irrigated only in certain regions.

2.3.2 **Identification of risk drivers**

By analysing which drought indicators are closely connected to the observed reductions in crop yield (see Annex I), the main hazard drivers for drought impacts for the different crops were revealed. The most common drought drivers for wheat and maize production losses are related to precipitation minus evapotranspiration deficits (top block of indices in Figure 6, including SPEI), also purely precipitation-based indices show a strong connection to losses (second block of indices, including precipitation and SPI). The extent of these meteorological drought variables is in line with the general rain-fed nature of the growing of wheat in Europe.

Looking into hazard connected with impact, the relationship for rice shows a strong dependence on minimum discharge, which is in line with its need for surface water irrigation during growth. A strong signal of minimum discharge is also visible for potato, which can be attributed to supplementary irrigation used to improve potato yield by around 10% to 20% in the main producing countries (Goffart et al 2022).

Lastly, barley shows a variety of drought indicators linked to yield reduction. Overall, the precipitation and evapotranspiration (top block) indices are generally the most important, but also minimum discharge is relatively important. Whilst barley is generally rain-fed, resulting in the high importance of many meteorological indices, it is often irrigated in dry areas. As such, the high relative importance of this index could be related to barley yield variability in southern Europe[1].

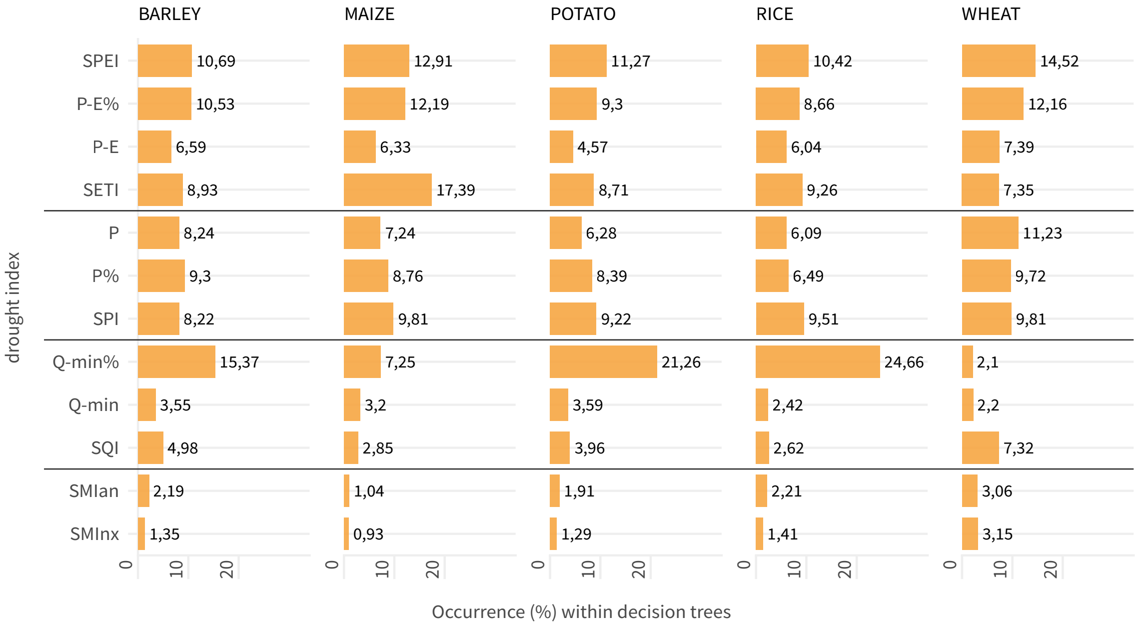

Figure 6: Occurrence of drought indices per crop in the decision trees. The group of indices related to precipitation (P) and evapotranspiration (E) is the most important for prediction of the impact on agriculture. The most important group for rice and potato (as irrigated crops) is discharge (Q)-related indices (see Annex I for details).

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[1] *In Europe (27 countries), the area given over to barley farming stands at around 12 million ha, with about 20% of the total area located in Spain. https://www.sciencedirect.com/science/article/pii/S0048969719359777. Barley is the most widely grown crop in Spain, with around 11 million Mg produced on 2.75 million ha, of which 0.36 million is irrigated.*

2.3.3 **Drought risk under current climate conditions**

Wheat

The largest average annual relative reduction in yield (in %) due to droughts is currently estimated to be in Spain, Romania, southern Italy and Cyprus (Figure 8).

Given the large amount of wheat production in some regions of Spain and Romania (Figure 7), this means that these countries are expected to also face the largest drought-induced absolute production losses. Northern Finland also shows a high average annual relative reduction in crop yield, but this number is largely influenced by the very limited wheat-cultivated area (very low exposure, Figure 7).

The map of 1-in-50-year drought loss (Figure 9) presents the same pattern of drought hotspots, but with the addition of Greece which is estimated to experience substantial losses (up to 50%) on average once every 50 years; whilst in north-western Europe losses stand mostly at about a 20% yield reduction are experienced at this return period.

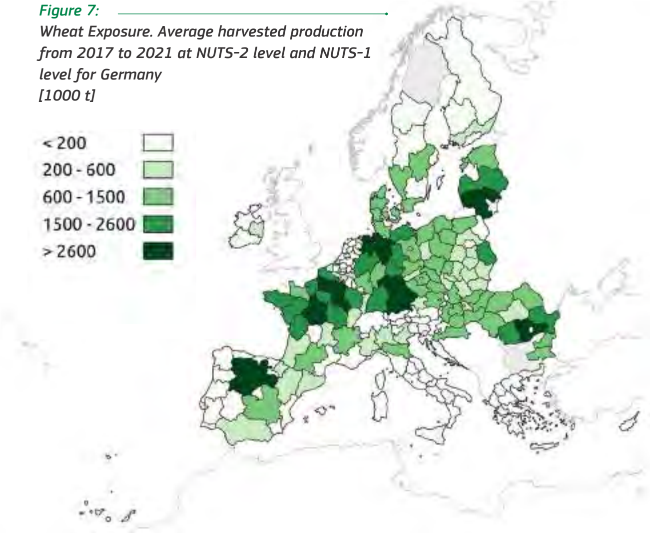


Figure 7:
Wheat Exposure. Average harvested production from 2017 to 2021 at NUTS-2 level and NUTS-1 level for Germany [1000 t]

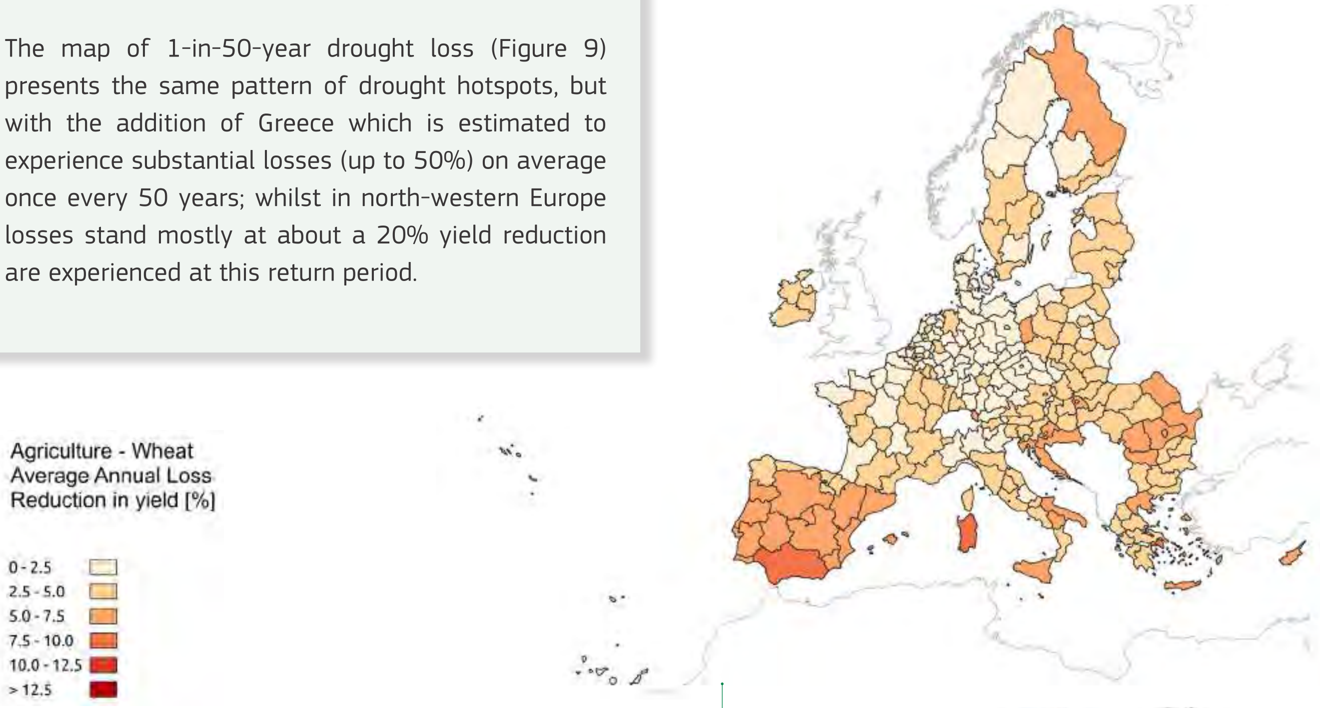
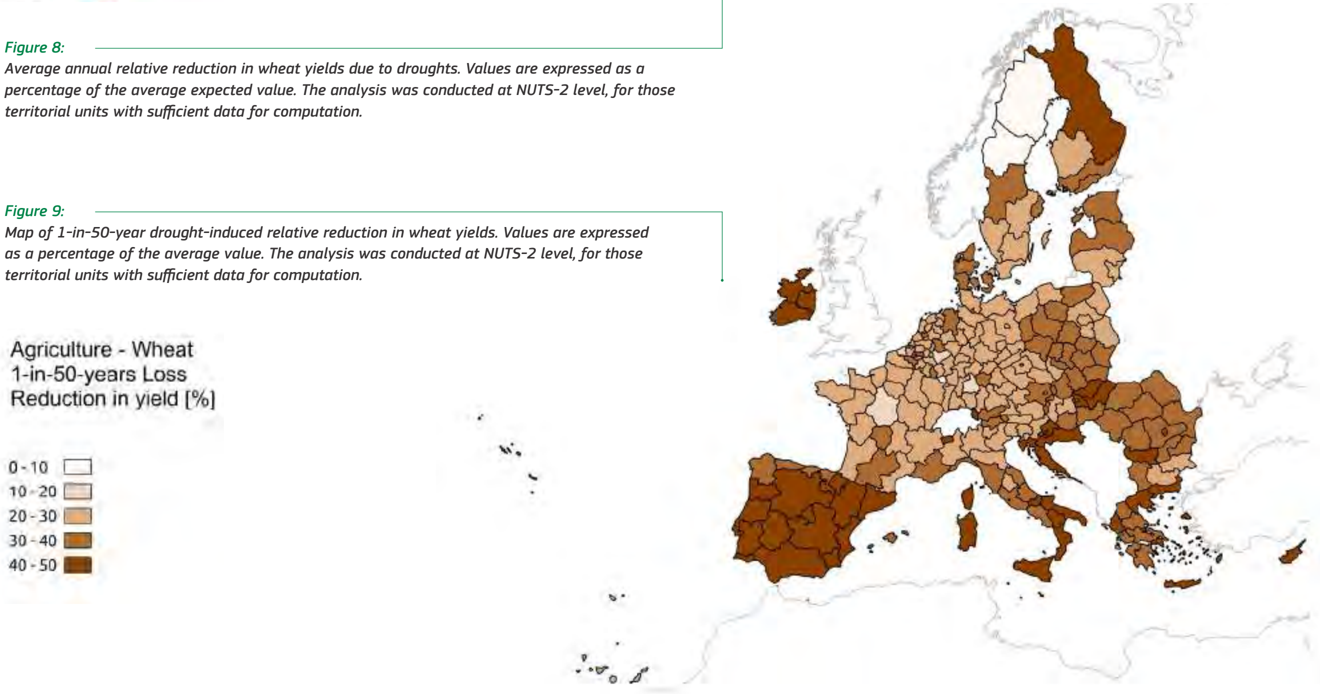


Figure 8:
Average annual relative reduction in wheat yields due to droughts. Values are expressed as a percentage of the average expected value. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.

Figure 9:
Map of 1-in-50-year drought-induced relative reduction in wheat yields. Values are expressed as a percentage of the average value. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.



Barley

The average annual relative reduction in yield (in %) due to droughts is estimated to be largest in Spain, Romania, followed by Greece and southern Italy. Due to the high values of exposure (Figure 10), Spain has also the highest level of risk in absolute terms.

Agricultural drought impact in northern Sweden is less relevant because of low exposure (low average barley crop yield), although this region may be extra susceptible to drought conditions due to the short growing season.

The map of 1-in-50-year drought loss, shows the probable reduction in yield for extreme events occurring on average once every 50 years, shows the same risk pattern with the addition of an area in eastern Germany and western Poland. As with drought risk for wheat production, losses can be substantial: up to 50% reduction at this recurrence interval.

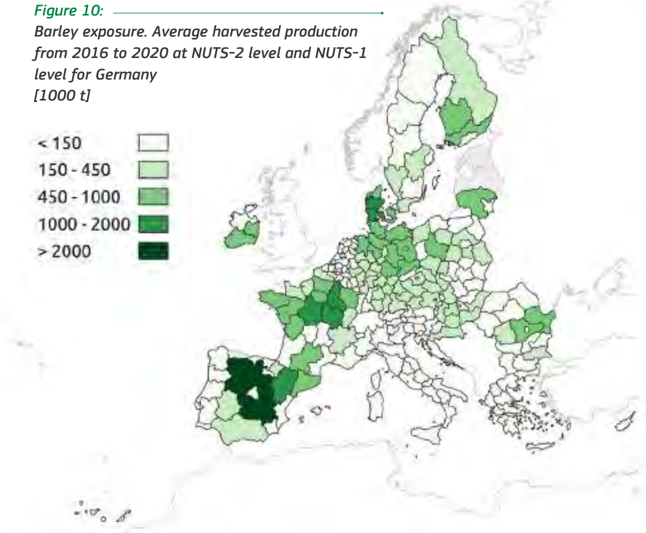


Figure 10:
Barley exposure. Average harvested production from 2016 to 2020 at NUTS-2 level and NUTS-1 level for Germany
[1000 t]

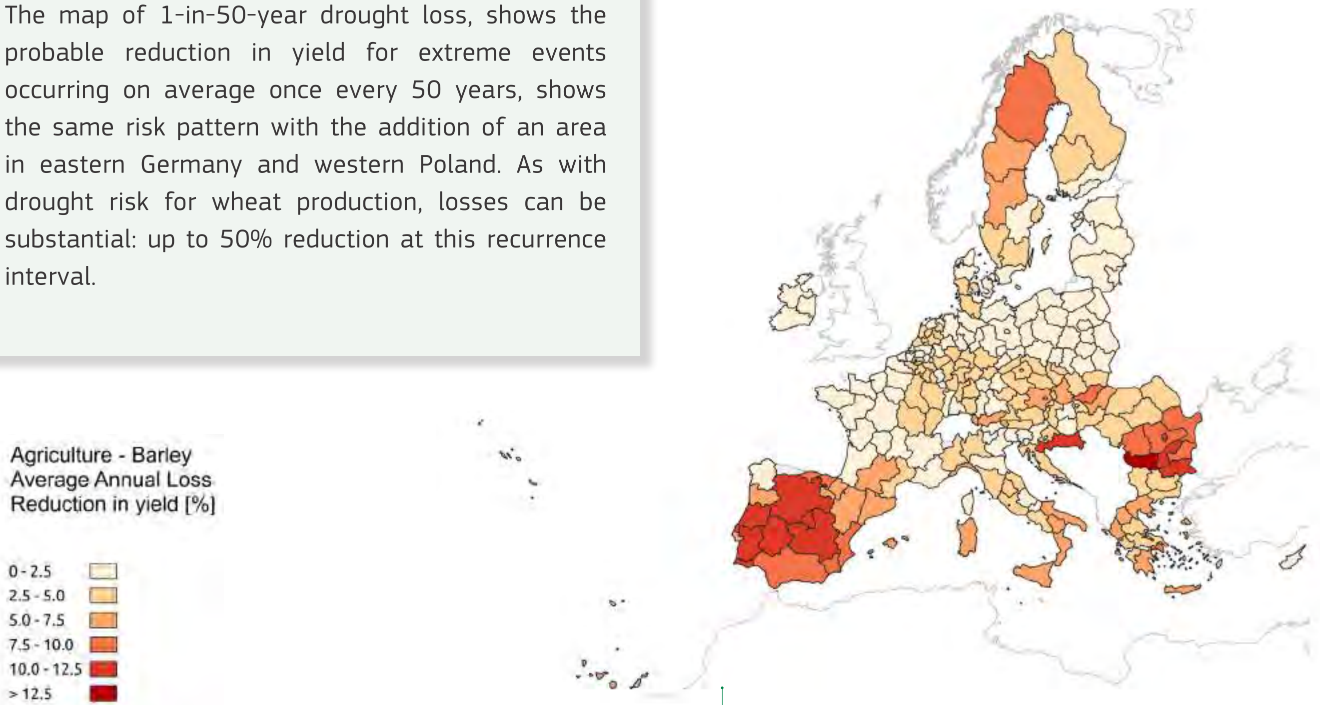
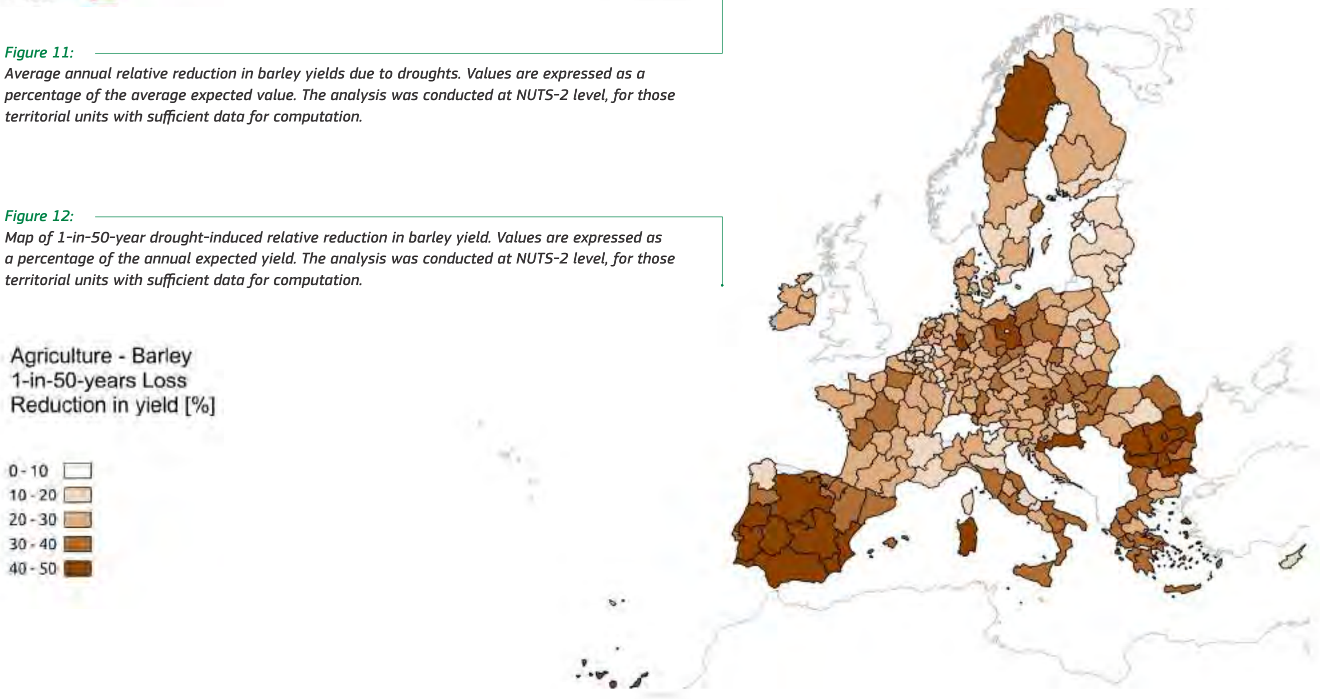


Figure 11:
Average annual relative reduction in barley yields due to droughts. Values are expressed as a percentage of the average expected value. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.

Figure 12:
Map of 1-in-50-year drought-induced relative reduction in barley yield. Values are expressed as a percentage of the annual expected yield. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.



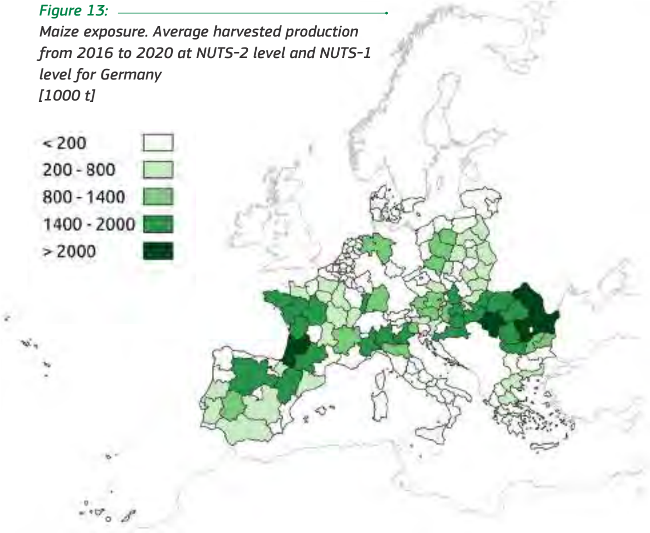
Maize

The average annual relative reduction in maize yield due to droughts is estimated to be largest in eastern Europe and especially in Romania (Figure 14), which has also a high level of exposure (Figure 13).

Consequently, Romania stands out as the primary focal point within the European Union for substantial maize production losses (in tonnes) caused by drought events. When considering the size of drought-induced losses at a 1-in50-year interval at NUTS-2 level (Figure 14), high relative yield reductions are expected in France and northern Italy as well.

Spatially, it is essential to underscore that maize exhibits relatively consistent patterns of drought-induced losses when compared to other crops.

Figure 13:
Maize exposure. Average harvested production from 2016 to 2020 at NUTS-2 level and NUTS-1 level for Germany [1000 t]



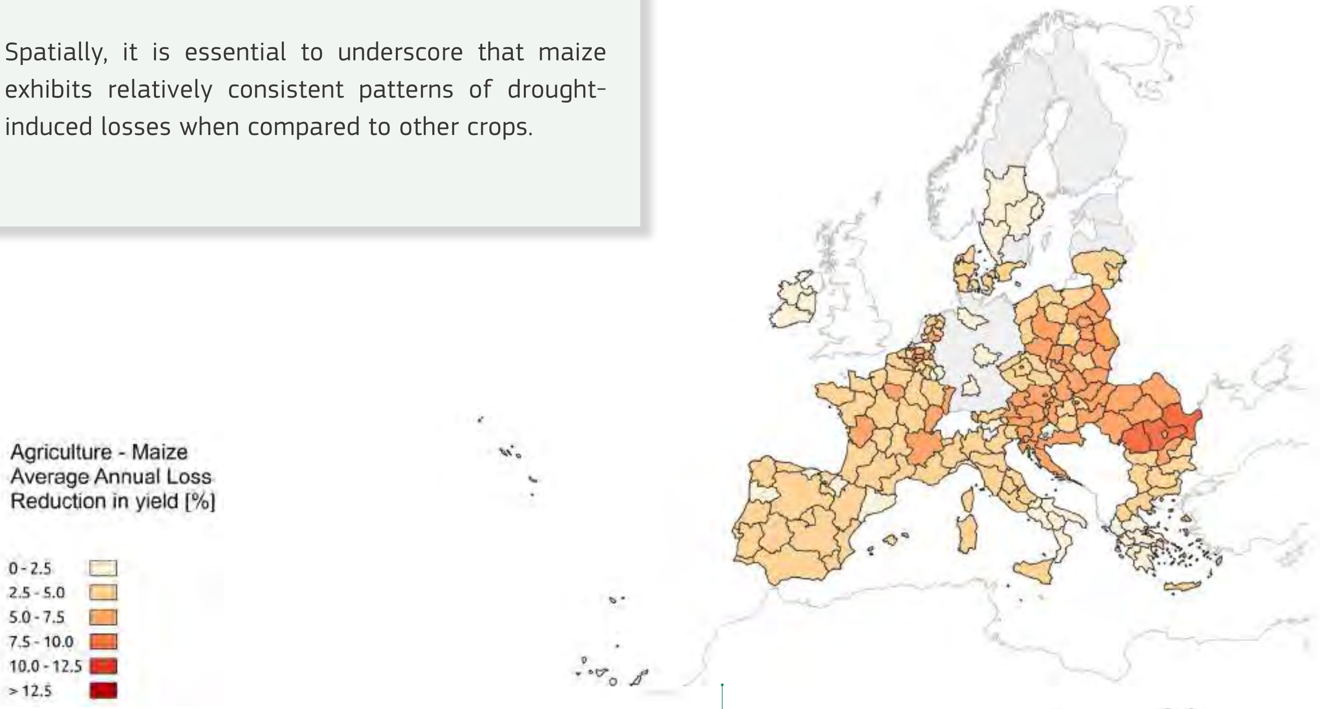
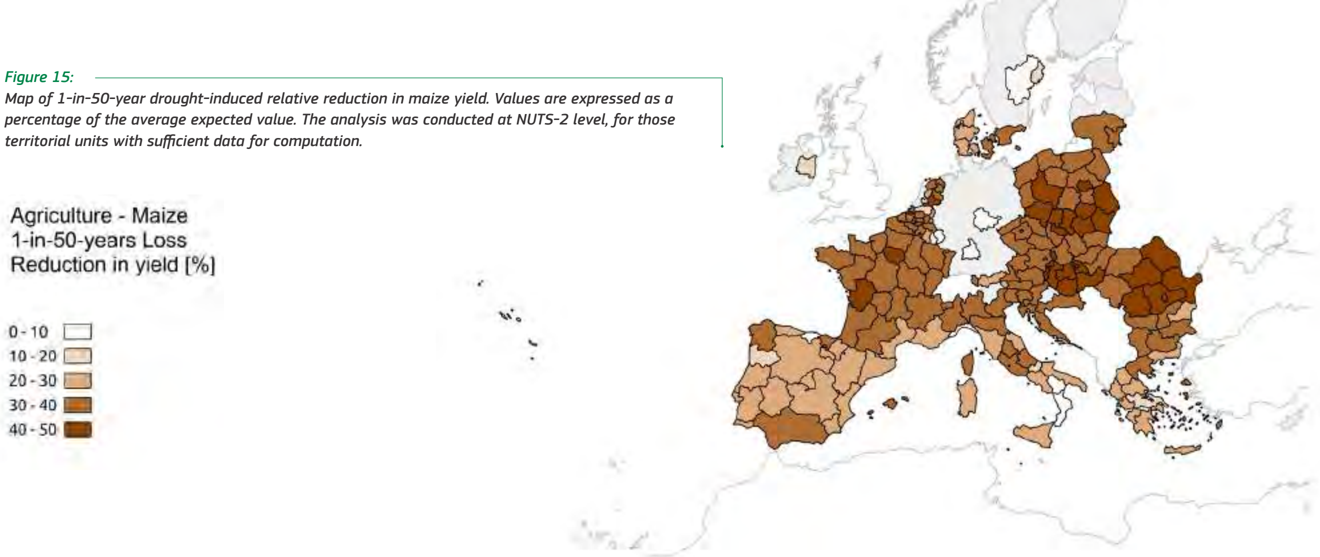


Figure 14:
Average annual relative reduction in maize yields due to droughts. Values are expressed as a percentage of the average expected value. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.

Figure 15:
Map of 1-in-50-year drought-induced relative reduction in maize yield. Values are expressed as a percentage of the average expected value. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.



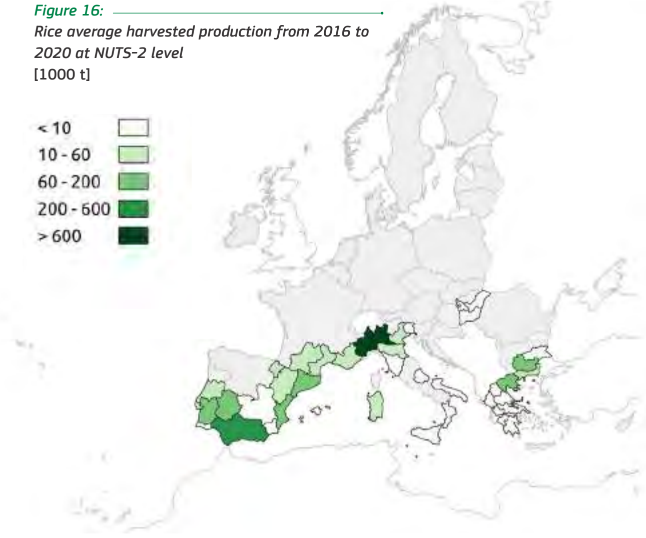
Rice

There is no clear spatial pattern in average annual relative reduction in rice yield (in %) due to droughts.

The largest relative losses under current climate conditions are estimated in Spain, southern France, central and southern Italy, Romania and Greece.

The same pattern is visible when considering 1-in-50-year events. At such recurrence intervals, drought-driven losses up to 40%-50% can be expected (Figure 17).

Figure 16:
Rice average harvested production from 2016 to 2020 at NUTS-2 level
[1000 t]



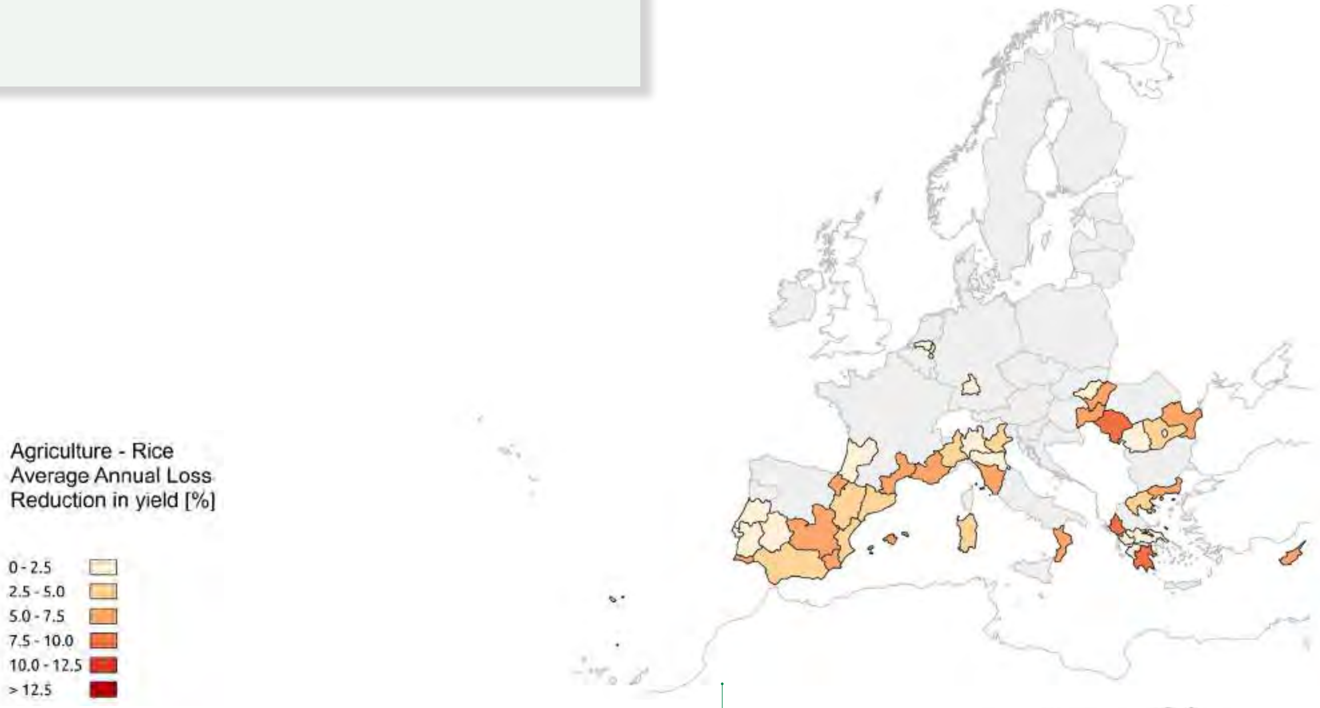
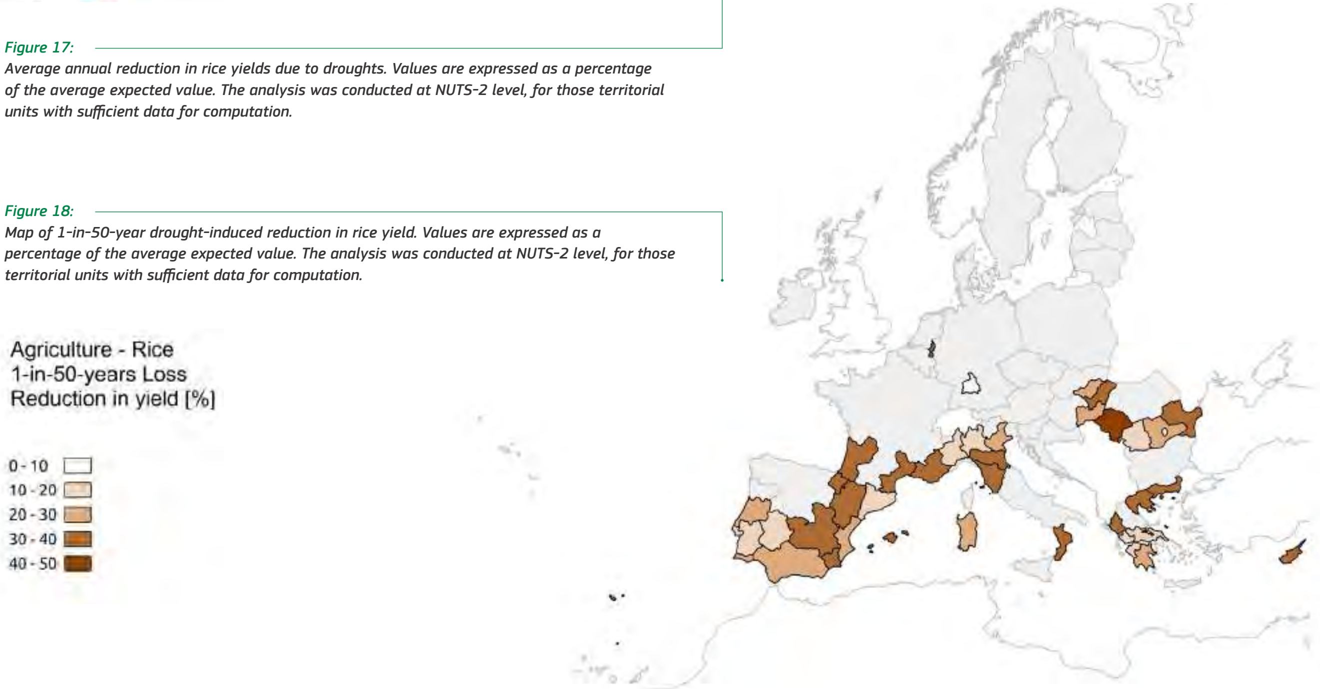


Figure 17:
Average annual reduction in rice yields due to droughts. Values are expressed as a percentage of the average expected value. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.

Figure 18:
Map of 1-in-50-year drought-induced reduction in rice yield. Values are expressed as a percentage of the average expected value. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.

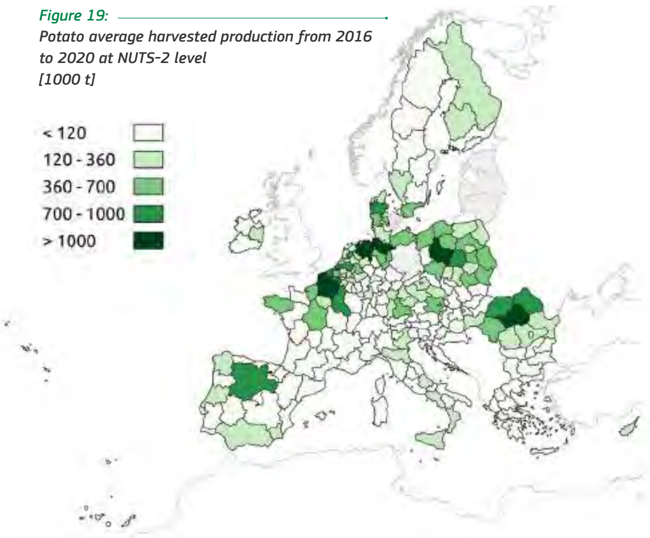


Potato

The average annual relative yield reduction (in %) due to droughts is relatively homogenous across Europe. Notable exceptions are northern Sweden and Finland (though exposure is low there, Figure 19), eastern Bulgaria and to some degree central/south Italy (Figure 20).

When considering extreme events occurring on average 1-in-50-years (Figure 21), high relative yield reductions are estimated in the same regions, and some other areas with high drought risk show up (e.g. in Portugal, France, and Slovakia).

Figure 19:
Potato average harvested production from 2016 to 2020 at NUTS-2 level [1000 t]



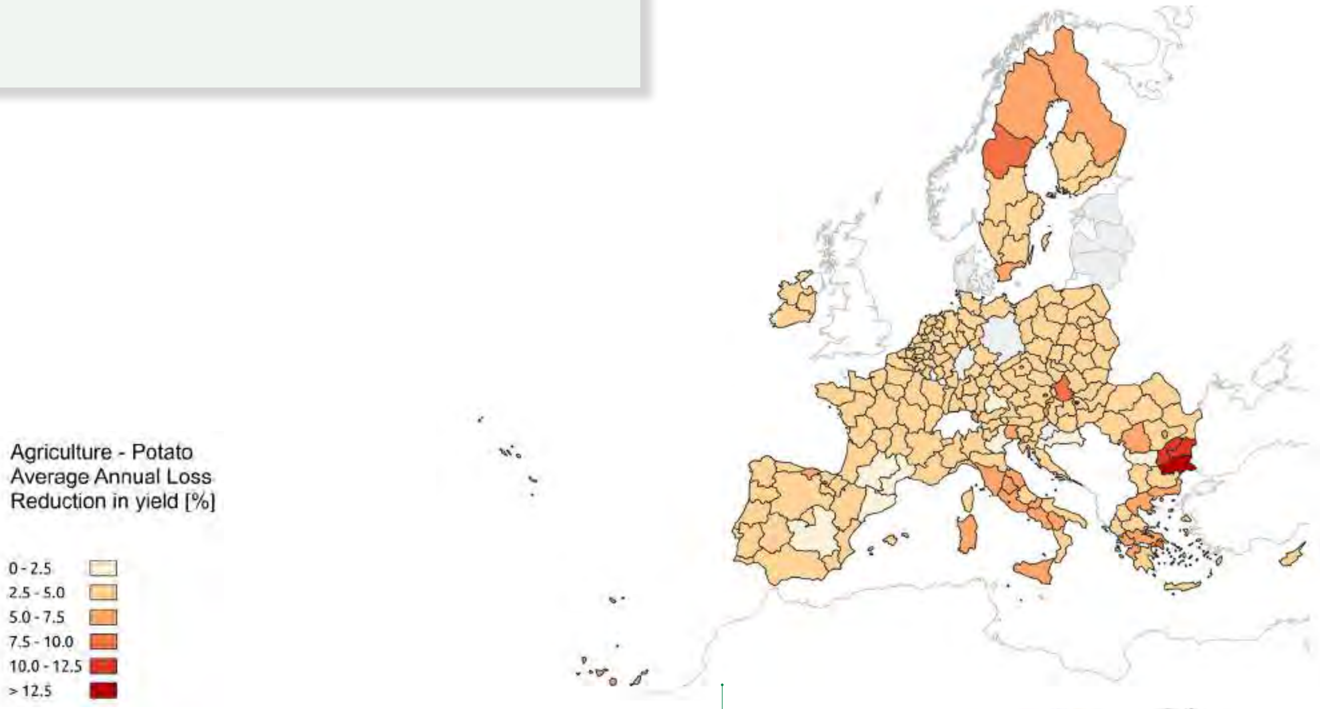
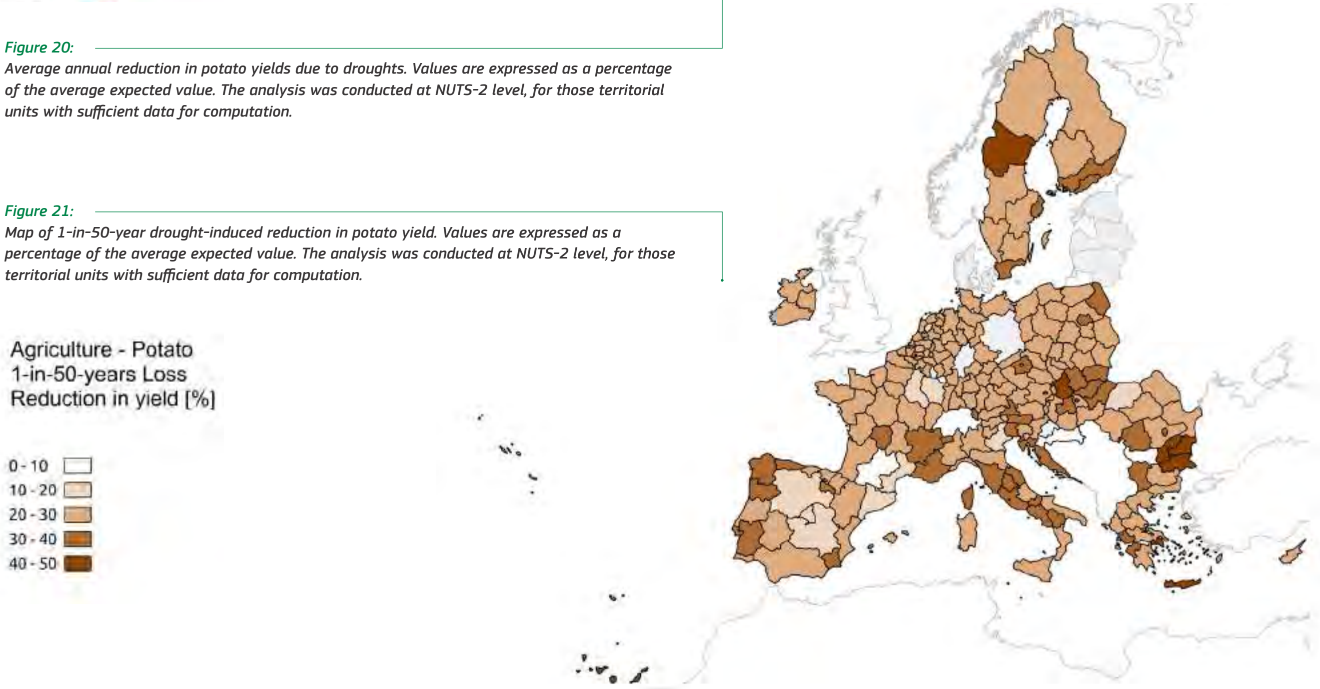


Figure 20:
Average annual reduction in potato yields due to droughts. Values are expressed as a percentage of the average expected value. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.

Figure 21:
Map of 1-in-50-year drought-induced reduction in potato yield. Values are expressed as a percentage of the average expected value. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.



2.3.4 Drought risk under projected climate conditions

Crops analysed under projected climate conditions

Future projections of drought impacts are considered for wheat, barley and maize. Future projections for rice and potato are not considered here as extrapolating the hazard-impact link to climate change scenarios was not possible, due to the nature of these crops (their irrigation share, their sensitivity to flood events) and limitations of future projections, for which only standardized indices can be used (indices related to absolute quantities of water are affected by biases of the climate models). Rice is an irrigated crop (and potato is too, to some extent), which is less well represented by standardised indices. Furthermore, rice (and potato, to a lesser degree), offers rather limited impact data for training the model. In addition, getting a good signal for potato is also more difficult given that wet events strongly affect potato yield.

Credits: © Sat123, via Wikimedia Commons

Wheat

Figure 22 shows that wheat yield losses due to droughts rise with increasing warming levels almost all over Europe. The largest variations are projected to occur in France and Germany, where yield losses increase up to three times with respect to the historical values. The large increase in central Europe indicates that even while on average drought indices may remain similar between the historical situation and future projection (Figures 67, 68, 69, 70 in Annex II), an increase in variability in weather conditions due to climate change can heavily influence drought losses. The already critical conditions in Spain due to high relative risk (Figure 8) and high exposure (Figure 7) may even worsen in the projected conditions especially in warming levels 2 °C and 3 °C, leading to very high levels of risk in absolute terms. The increase in yield losses in northern Finland is less relevant because of very low exposure. In the Baltic region, drought-induced wheat losses should noticeably fall, due to the wetting (precipitation and soil moisture) estimated by the climate models for this region. Generally, yield losses will increase under climate change for more extreme events (e.g. a 6.5%-8% reduction during a 1-in-50-year event) at the European level, as can be seen in the PML curves. The potential benefits of increased atmospheric CO_2 concentration are here not taken into account.

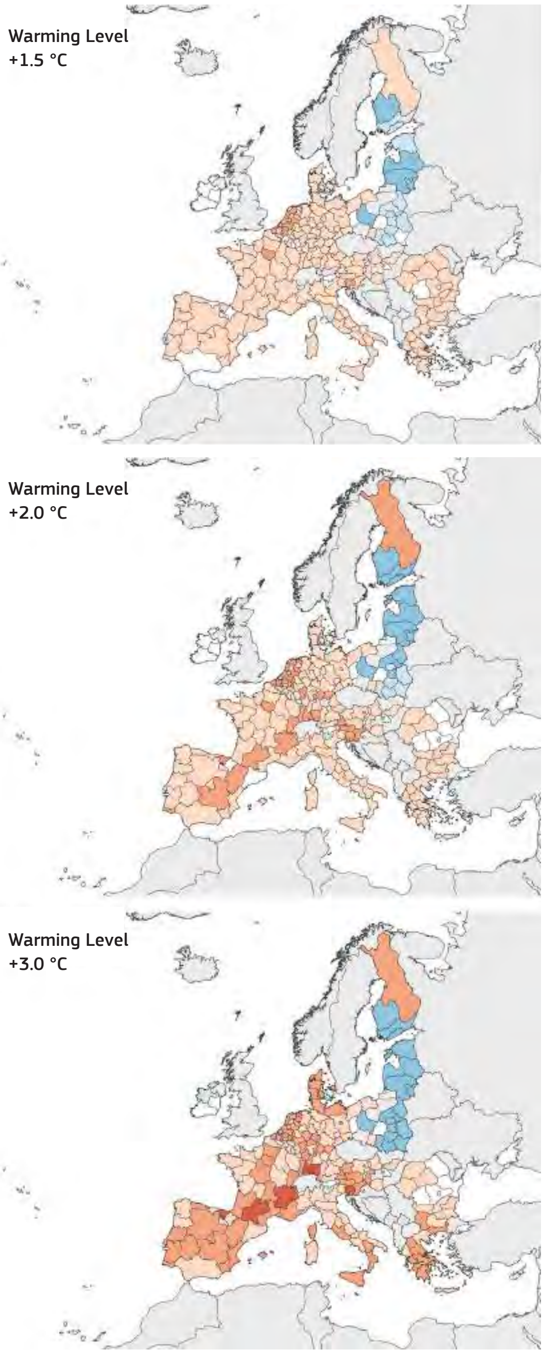


Figure 22:

Variation in drought risk for wheat production between current and projected conditions. Risk is measured as average annual yield reduction compared to the average expected value under current conditions. Results of future simulations forced with 11 climate models in RCP 4.5 and RCP 8.5 are averaged for each warming level (+1.5 °C, +2.0 °C, +3.0 °C). The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.

Projected Loss / Current Loss

- 🟦 reduction of more than 25%
- ▨ reduction between 10% and 25%
- ☐ no important variation
- ▨ increased by a factor of 1.1 to 1.5
- ▨ increased by a factor of 1.5 to 2
- 🟥 increased by a factor of 2 to 3
- 🟥 increased by a factor of 3 to 4
- ■ increased by a factor of more than 4

Probable Maximum Loss (PML) curves

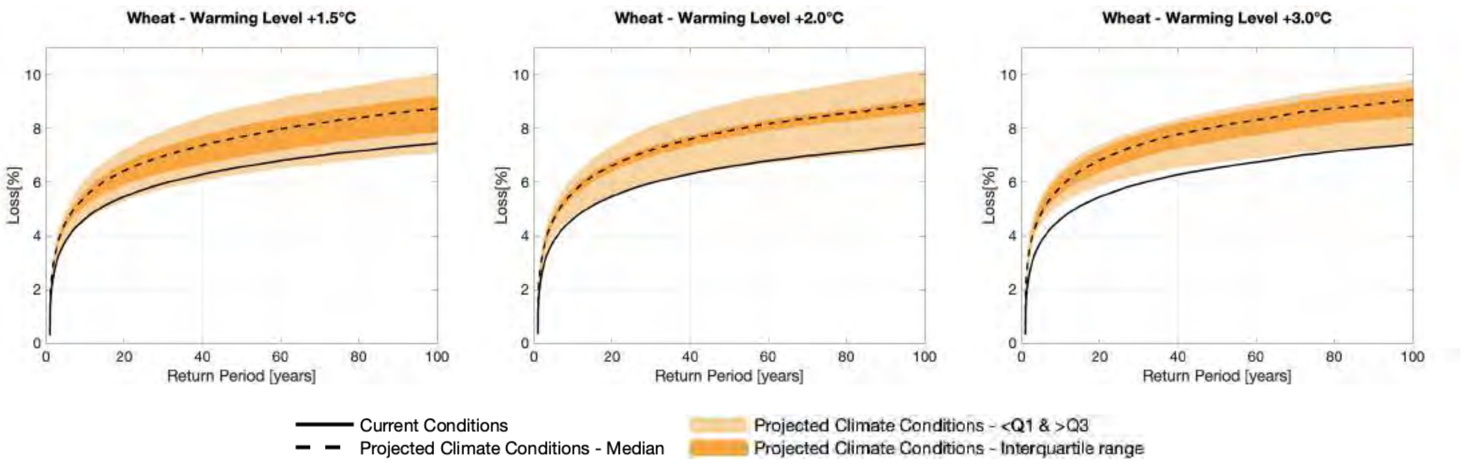


Figure 23:

EU-aggregated PML curves for wheat yield under current and projected conditions for +1.5 °C, +2.0 °C, +3.0 °C warming level scenarios. The solid black line is the PML curve for the historical period, while the dotted black line traces out the median of future simulations forced with 11 climate models in both RCP 4.5 and RCP 8.5. The shades of yellow denote the climatic variability of future simulations: dark yellow is the interquartile, while pale yellow represents the lower and upper quarters.

Barley

In relative terms losses rise with increasing warming levels mainly in the Mediterranean region. Similar to what happens for wheat, the already critical conditions of Spain are projected to worsen. Here the largest relative increases are projected to occur in Spain with yield losses up to three times the losses experienced under current climate conditions. In the Baltic region wheat losses caused by drought may fall, due to the wetting (precipitation and soil moisture) estimated by the climate models for this region.

Generally, relative yield losses at the European level will increase slightly under climate change; however, the projections vary significantly, as can be seen in (the uncertainty around) the PML curves (Figure 25) representing the maximum drought-induced crop losses expected for different return periods under the three projected warming levels.

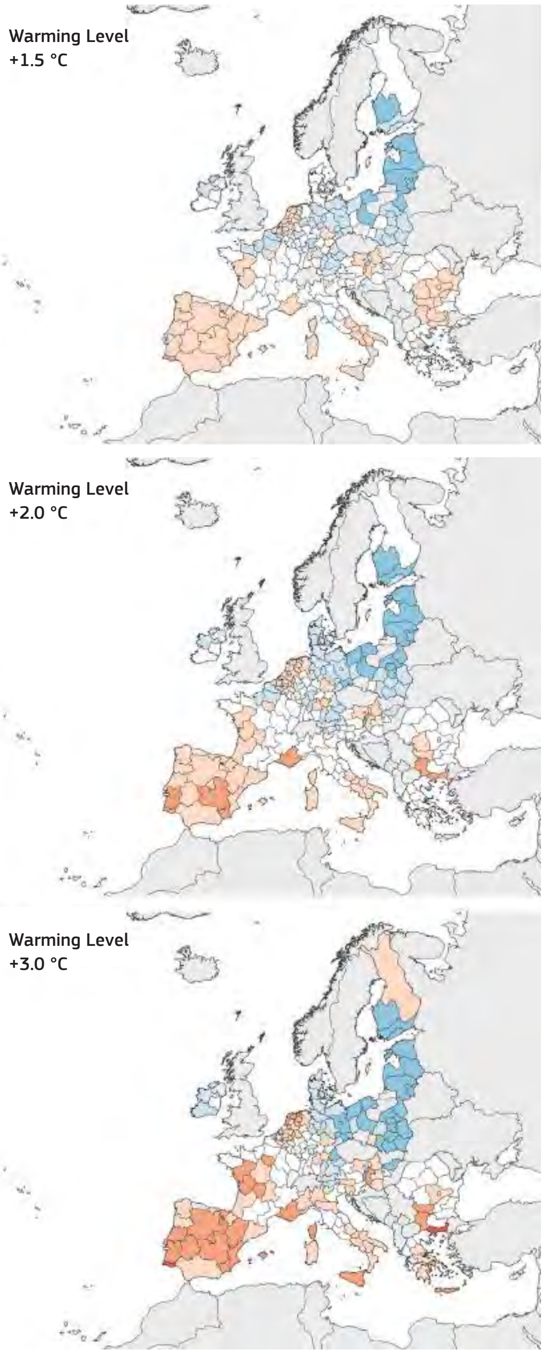


Figure 24:
Variation in drought risk for barley production between current and projected conditions.
Risk is measured as average annual yield reduction compared to the average expected value under current climate conditions. Results of future simulations forced with 11 climate models in RCP 4.5 and RCP 8.5 are averaged for each warming level (+1.5 °C, +2.0 °C, +3.0 °C). The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.

Projected Loss / Current Loss

🟦 reduction of more than 25%
🟦 reduction between 10% and 25%
⬜ no important variation
🟧 increased by a factor of 1.1 to 1.5
🟧 increased by a factor of 1.5 to 2
🟥 increased by a factor of 2 to 3
🟥 increased by a factor of 3 to 4
🟫 increased by a factor of more than 4

Probable Maximum Loss (PML) curves

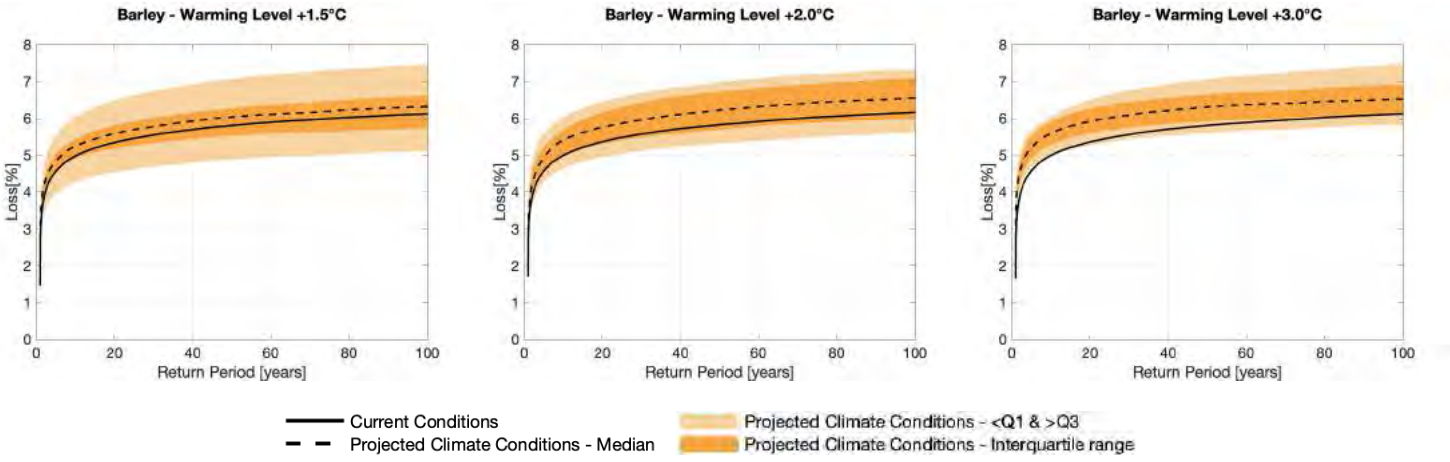


Figure 25:
EU-aggregated PML curves for barley yield due to droughts under current and projected climate conditions for +1.5 °C, +2.0 °C, +3.0 °C warming level scenarios.
The solid black line is the PML curve for the historical period, while the dotted black line traces out the median of future simulations forced with 11 climate models in both RCP 4.5 and RCP 8.5.
The shades of yellow denote the climatic variability of future simulations: dark yellow is the interquartile, while pale yellow represents the lower and upper quarters.

Maize

In relative terms, maize yield losses rise with increasing warming levels mainly in the Mediterranean region.
The largest relative increases are projected to occur in Spain, Italy and Bulgaria with yield losses up to three times the losses experienced under current climate conditions.
In Poland maize losses due to drought may fall, in connection with the wetting (precipitation and soil moisture) estimated by the climate models for this country (Figure 26).

Generally, the relative yield losses expected to be experienced at different return periods will increase at European level under climate change: probable maximum losses are projected to be higher under higher warming levels, but there is a wide variety in the projections, as can be seen in the PML curves (Figure 27).

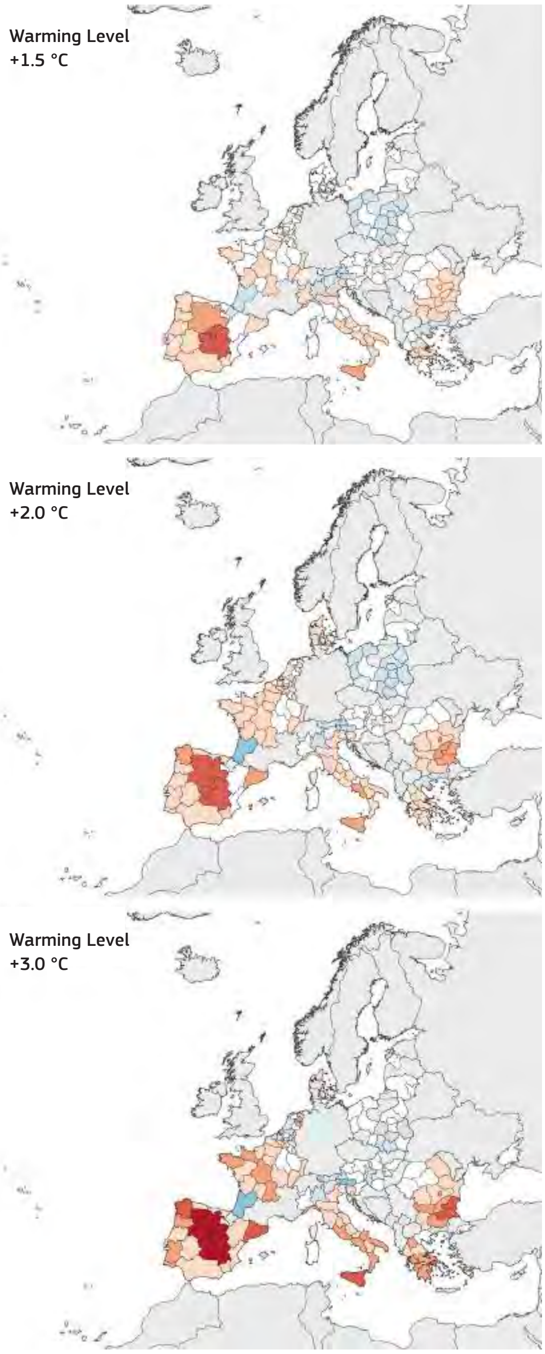


Figure 26:
Variation in drought risk for maize production between current and projected conditions. Risk is measured as average annual yield reduction compared to the average expected value under current climate conditions. Results of future simulations forced with 11 climate models in RCP 4.5 and RCP 8.5 are averaged for each warming level (+1.5 °C, +2.0 °C, +3.0 °C). The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.

Projected Loss / Current Loss

- 🟦 reduction of more than 25%
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- 🟧 increased by a factor of 1.5 to 2
- 🟥 increased by a factor of 2 to 3
- 🟥 increased by a factor of 3 to 4
- ■ increased by a factor of more than 4

Probable Maximum Loss (PML) curves

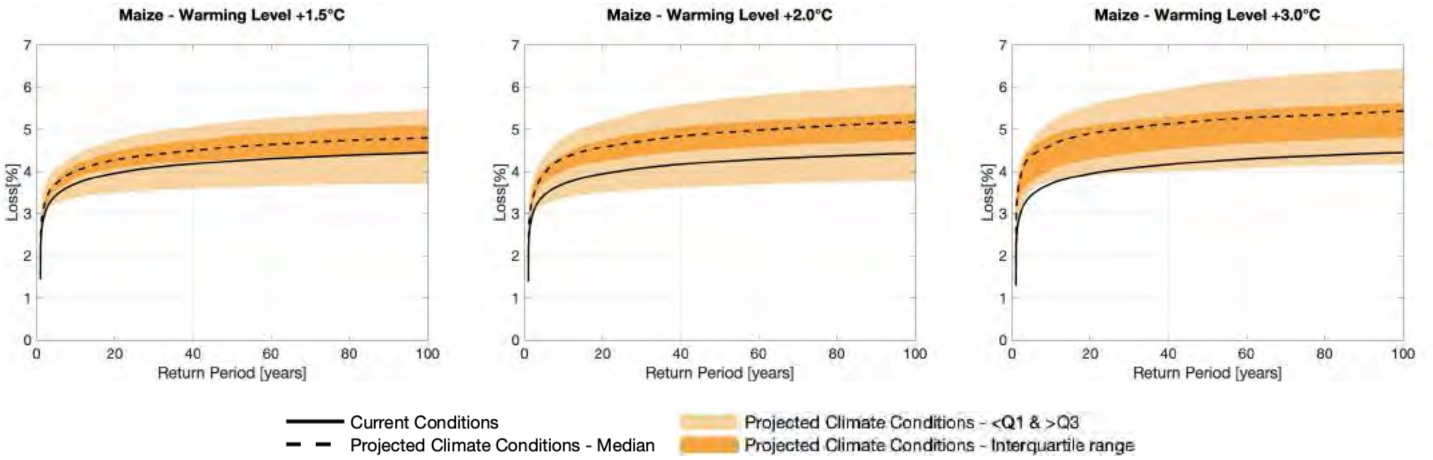

Figure 27:
EU-aggregated PML curves for maize under current and projected conditions for +1.5 °C, +2.0 °C, +3.0 °C warming level scenarios. The solid black line is the PML curve for the historical period, while the dotted black line traces out the median of future simulations forced with 11 climate models in both RCP 4.5 and RCP 8.5. The shades of yellow denote the climatic variability of future simulations: dark yellow is the interquartile, while pale yellow represents the lower and upper quarters.

CHAPTER 3

Public water supply

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3.1 Key facts

The public water supply system in the European Union is responsible for providing about 474 million citizens with an average of 156 litres per day of high-quality water for consumption (European Commission 2016). The system consists of around 11,000 large and 85,000 small supplies, which serve 80% and 20% of the population respectively. The freshwater abstracted for this system comes in roughly equal amounts from groundwater and surface water sources. The drinking water is then provided to households by publicly owned enterprises in more than 60% of the EU water infrastructure (Council of the European Union 2016), whereas the remainder is provided by regulated entities with different levels of private ownership. Safe drinking water is not only essential for public health, but also economically important, as it is a precondition for the development of economic activities. Therefore, decreased quantities of adequate quality water can have high social and economic costs for the EU.

Drought events can reduce groundwater and surface water levels, which are the main sources of drinking water in the EU. This decrease affects water availability, and, at times, the level of water quality required of fresh water for public water supply. The recent 2022 drought event affected the water supply capacity of various municipal areas in Europe. For example, more than 100 of these in France had water supply issues and drinking water had to be delivered by truck (Toreti et al. 2022) while water use was restricted in nearly all metropolitan departments of France. In Italy too, local authorities restricted water use during the summer of 2022[1].

Credits: © F. Muhammad - Pixabay

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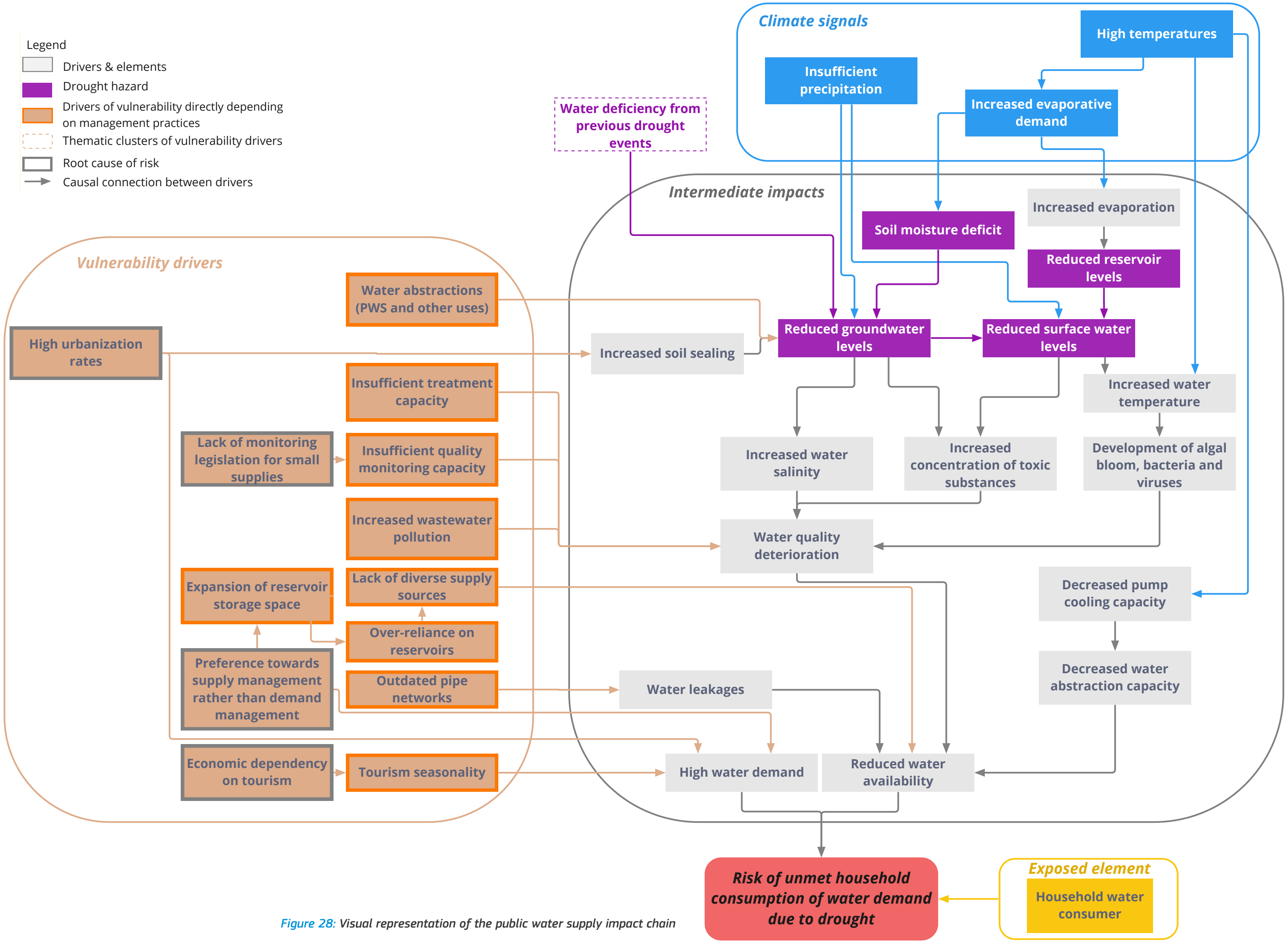
[1] *https://www.repubblica.it/green-and-blue/2022/06/23/news/siccita_le_regioni_e_i_comuni_chiudono_i_rubinetti-355047552/*

Impact Chain – Public water supply



Legend
- ▭ Drivers & elements
- 🟪 Drunk hazard
- 🟧 Drivers of vulnerability directly depending on management practices
- ⬚ Thematic clusters of vulnerability drivers
- ▭ Root cause of risk
- → Causal connection between drivers

Climate signals

High temperatures

Insufficient precipitation

Increased evaporative demand

Water deficiency from previous drought events

Intermediate impacts

Increased evaporation

Soil moisture deficit

Reduced reservoir levels

Reduced groundwater levels

Reduced surface water levels

Increased soil sealing

Increased water temperature

Increased water salinity

Increased concentration of toxic substances

Development of algal bloom, bacteria and viruses

Water quality deterioration

Decreased pump cooling capacity

Decreased water abstraction capacity

Water leakages

High water demand

Reduced water availability

Vulnerability drivers

Water abstractions (PWS and other uses)

High urbanization rates

Insufficient treatment capacity

Lack of monitoring legislation for small supplies

Insufficient quality monitoring capacity

Increased wastewater pollution

Expansion of reservoir storage space

Lack of diverse supply sources

Over-reliance on reservoirs

Preference towards supply management rather than demand management

Outdated pipe networks

Economic dependency on tourism

Tourism seasonality

Risk of unmet household consumption of water demand due to drought

Exposed element

Household water consumer

Figure 28: Visual representation of the public water supply impact chain

Risk (public water supply)

Drought events can affect the availability of water for household supply, both in terms of water quantity and quality, as previous droughts in Europe have shown (Van Lanen et al. 2016; Ahopelto et al. 2019; Bangash et al. 2013). For this reason, the risk for the public water supply system is defined here as the risk of household consumption water demand not being met due to drought. This encompasses both the possibilities that water availability is too low, either because of water quantity or quality, and that demand is too high, ultimately leading to unmet demand.

Exposed elements

The risk of unmet water demand poses a threat to the household water consumer, whose water is generally supplied by water supply companies and has to comply with the European Drinking Water Directive (European Commission 2014).

Climate signals & Hazards

The risk that household water demand is not met emerges during droughts due to the combination of insufficient precipitation and high temperatures.

Insufficient precipitation results in reduced groundwater and lower surface water levels in the streams and reservoirs that are used as sources for drinking water production, with accumulated water deficiency from previous drought events acting as a stressor in this situation (Van Lanen et al. 2016). At the same time, high temperatures further reduce recharge potential by causing increased evaporation. Moreover, they can also be responsible for the decreased pump cooling capacity of the pumps used to extract water, and this may cause decreased water abstraction capacity. These climate signals and hazards can also negatively affect water quality. Water in lower volumes often has an increased concentration of toxic substances. In addition, increased water temperature due to high air temperatures is connected to the development of algal blooms and growth of bacteria. Reduced water levels can also contribute to saltwater intrusion, which leads to increased water salinity and resulting quality deterioration (Van Lanen et al. 2016; Mullin 2020). All these processes decrease water availability for provision, as a certain degree of quality is required for household consumption.

Vulnerability drivers & Intermediate impacts

Many societal drivers can aggravate the situation for the public water supply system. For instance, increased soil sealing, driven by high urbanization rates, hinders groundwater recharge. In addition, higher demands by other sectors, such as agriculture or industry, contribute to reduced water availability for drinking purposes (Flörke et al. 2018). The public supply system suffers further losses during distribution due to outdated pipe networks (Ahopelto et al. 2019), which cause water leakages. Pipes can also suffer stress from dried-out soils, which can contribute to pipe bursts. However, this may be countered by the lower pressure from water inside the pipes. The problem of reduced water availability during droughts is exacerbated by a lack of diversity in supply sources (Mullin 2020), which ultimately requires more efficient water use and allocation (Mereu et al. 2016). The quality of the water available for public supply is also a concern during droughts, as the concentration of contaminants may increase as less water is available to dilute them. Sources of contamination can be societal such as wastewater pollution (WHO Regional Office for Europe 2022). In some cases, insufficient water treatment capacity can prevent this water from getting treated back to a level that is appropriate for consumption. This can generate increases in costs, as purification and monitoring procedures become more frequent and expensive. However, in specific cases, it may also pose a threat to human health if there is insufficient quality monitoring capacity to prevent this water from being provided to households (European Commission 2014), especially in the case of small or unofficial supplies, where insufficient monitoring may also stem from a lack of legislation (European Commission 2014; Gunnarsdottir et al. 2017). Finally, dynamic aspects that lead to high water demand also contribute to this risk. For instance, high urbanization rates can increase local risk (McDonald et al. 2014; Mereu et al. 2016). In addition, tourism seasonality can increase demand concentration in certain places and for certain periods of time (Martínez-Ibarra 2015; Mereu et al. 2016). Especially those places that show an economic dependency on tourism may be reluctant to introduce restrictions (Mereu et al. 2016), which may drive water planners to pursue the expansion of reservoir storage space, rather than take measures to control high demand. The expansion of reservoir storage contributes to an over-reliance on reservoirs: this policy can heighten the system's vulnerability to water shortages, as it undermines the incentive to pursue other adaptation actions against droughts (Di Baldassarre et al. 2018).

3.3 **Data-driven model results**

3.3.1 **Identification of available impact data**

The impact chain identified the main risk for this sector as the risk of decreased or increased household consumption water demand due to drought . The former is a result of drought-induced water shortage causing restrictions on domestic use, the latter results from higher demand and thus potentially challenges water providers to supply this increased demand. As impact proxy for water supply, Eurostat data on the annual renewable freshwater for each river basin district were used. More specifically, this is the amount of water abstraction for public water supply in million cubic meters per year at river basin district level, which was reconverted to NUTS-2 regions. The temporal coverage was a period of 21 years, from 2000 to 2020; however, there were large differences in available data between countries. Portugal and Finland lacked impact data, while data for Spain were only available for a four-year period (2011-2014). Italy also provided a fragmented dataset. Details of input data are reported in Annex II – Water Supply.

3.3.2 **Identification of risk drivers**

To understand historical drivers for reductions in water supply, a wide variety of drivers seems to be relevant, given the relatively equal occurrence of different drought indices (Figure 29). Water supply can come from various sources (groundwater and surface water). These are governed by different hydrological processes and therefore drought impacts on water supply are related to different indices representing drought in different parts of the hydrological cycle. the groups of indices related to precipitation and evapotranspiration, precipitation (alone), and discharge all play an important role. The index that stands out the most is the standardised “precipitation minus potential evapotranspiration” index. This index can be seen from a hydroclimatic perspective as an indicator of water stress. It represents the total amount of water, which, after an optimal evapotranspiration process, i.e. where plants have unlimited water availability, would replenish surface water or infiltrate to recharge aquifers, these being the two main sources of water abstraction.

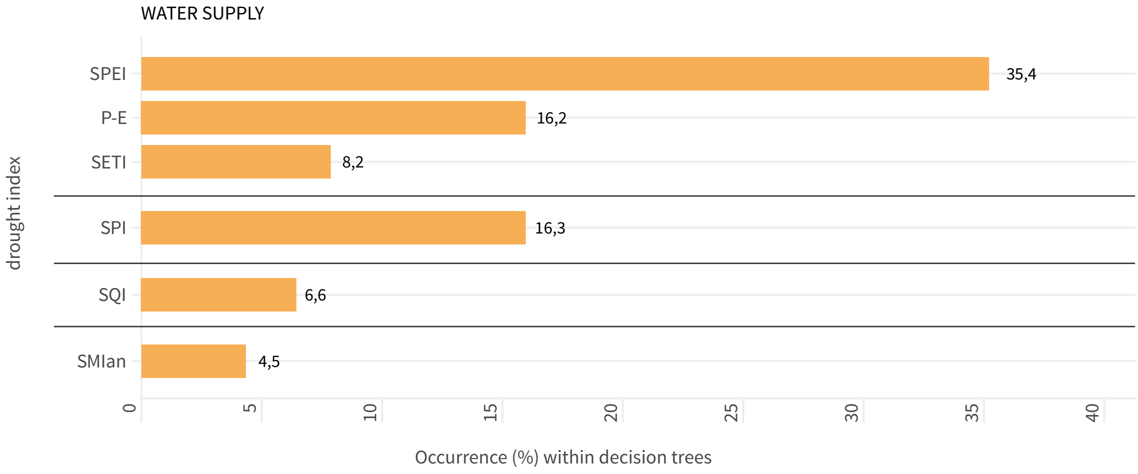
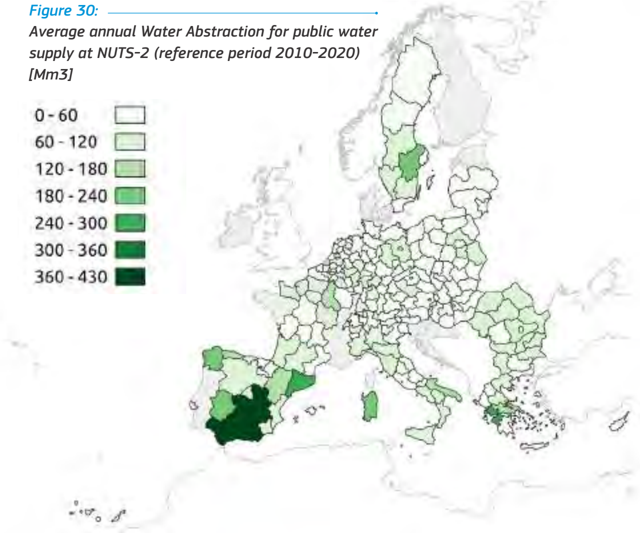


Figure 29:
Occurrence of drought indexes for water supply in the decision trees.
The group of indices related to Precipitation (P) and Evapotranspiration (E) - followed by Precipitation (P) alone and Streamflow (Q) - plays an important role for impact prediction on water supply (see Annex I for details).
Occurrence of other indices not showed here is about 1%.

3.3.3 **Drought risk under current climate conditions**

When looking into the drought risk for public water supply (Figure 31), we see demand for additional average annual water abstraction of up to 10%. These additional abstractions can pose challenges to suppliers in terms of treating and supplying water. The highest extra abstractions in the most water-rich countries (Scandinavia) which have enough water to face such extra abstractions relatively easily. We can also observe slightly elevated values (up to 5% extra abstractions) in dry southern regions. Here regular demand is probably much closer to the maximum supply of freshwater resources (highest level of abstraction in southern Spain, Figure 30), meaning there is less room to accommodate extra abstractions. Here it is likely that no further extra abstraction can take place during severe drought events and restrictions may come into force.

Figure 30:
Average annual Water Abstraction for public water supply at NUTS-2 (reference period 2010-2020) [Mm3]



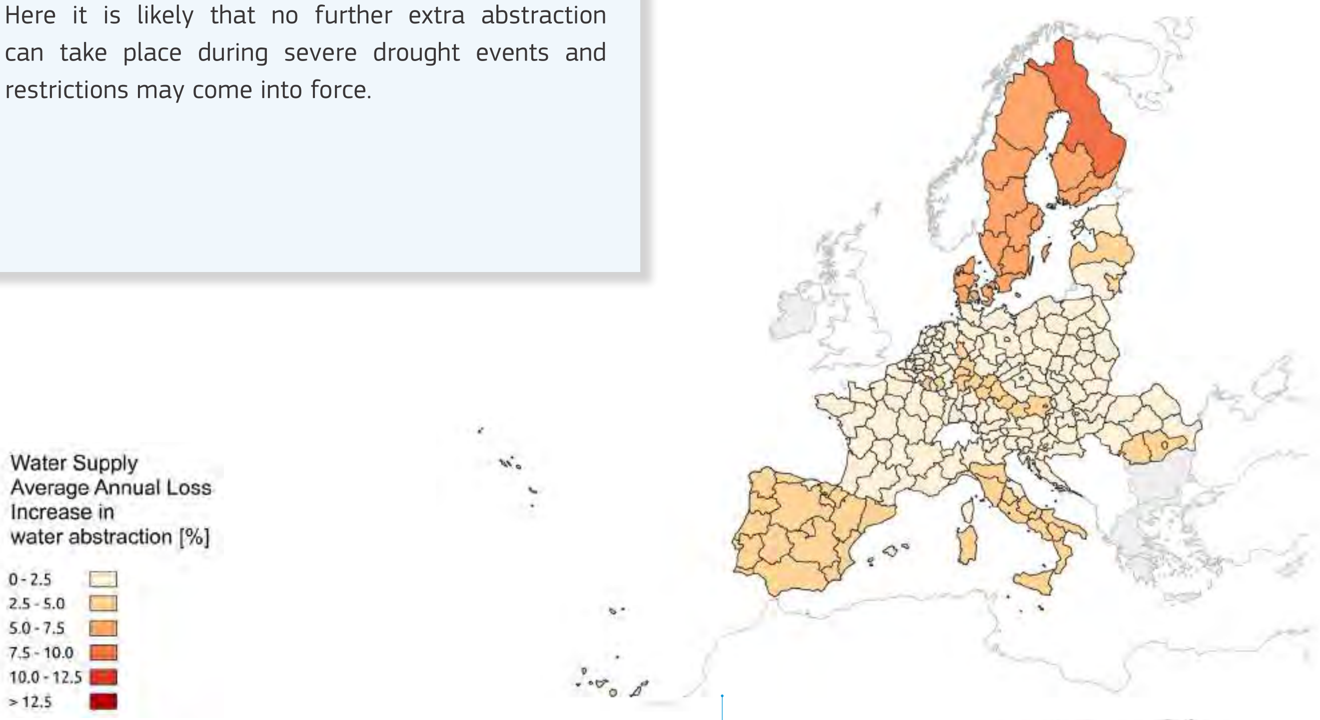
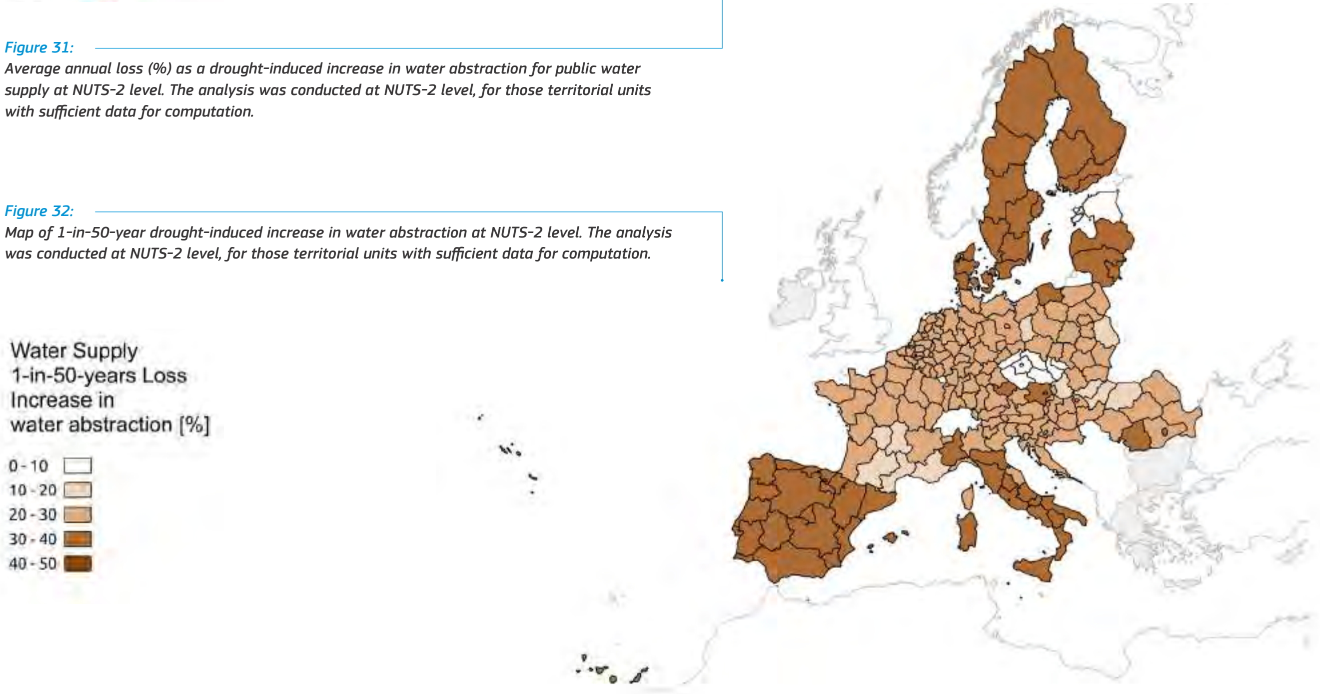


Figure 31:
Average annual loss (%) as a drought-induced increase in water abstraction for public water supply at NUTS-2 level. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.

Figure 32:
Map of 1-in-50-year drought-induced increase in water abstraction at NUTS-2 level. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.



3.3.4 **Drought risk under projected climate conditions**

In relative terms, risk is projected to increase (Figure 33) in almost all Europe and especially around the Mediterranean, where large increases in drought-induced water abstractions can be expected. Considering the level of exposure, Spain would be the most affected country with great relative increase in abstraction especially in warming level +2 °C and +3 °C. This may lead to increased competition on water resources, additional stress to water providers and potential restrictions on domestic water use or even taps running dry if demand cannot be met. The latter is likely in the Mediterranean region, since in that area there is also currently a link (not shown here) between drought events and reductions in water abstractions, illustrating that even usual demand cannot be met during current extremes. However, given the few precedents of taps running dry in other regions, the model could not project drought-induced reductions in water abstractions under projected climate change conditions on a European scale (due to model uncertainty).

The PML curves (Figure 34) show a slight rise in risk of increased abstractions with higher warming levels at European scale. Whether this would result in actual increases depends on whether policies on water restrictions and allocation priorities change.

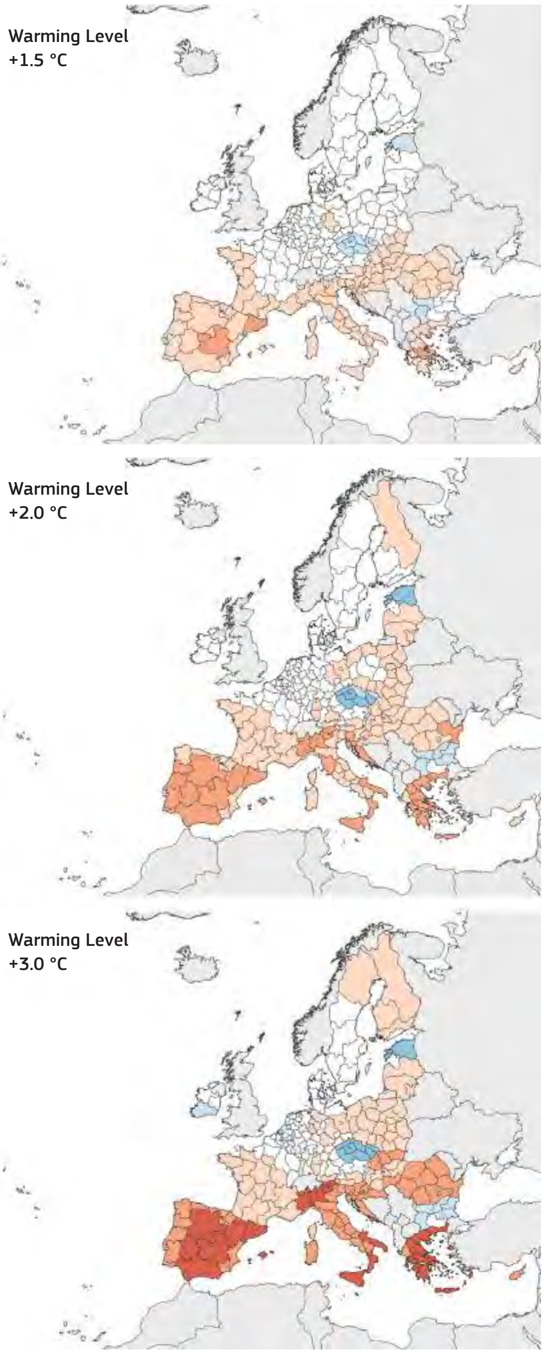


Figure 33:

Variation of drought risk for water supply between current and projected climate conditions. Risk is measured as average annual increase in drought-induced abstraction compared to the average expected value under current climate conditions. Results of future simulations forced with 11 climate models in RCP 4.5 and RCP 8.5 are averaged for each warming level (+1.5 °C, +2.0 °C, +3.0 °C). The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.

Projected Loss / Current Loss

- 🟦 reduction of more than 25%
- 🟦 reduction between 10% and 25%
- ☐ no important variation
- 🟧 increased by a factor of 1.1 to 1.5
- 🟧 increased by a factor of 1.5 to 2
- 🟥 increased by a factor of 2 to 3
- 🟥 increased by a factor of 3 to 4
- 🟥 increased by a factor of more than 4

Probable Maximum Loss (PML) curves

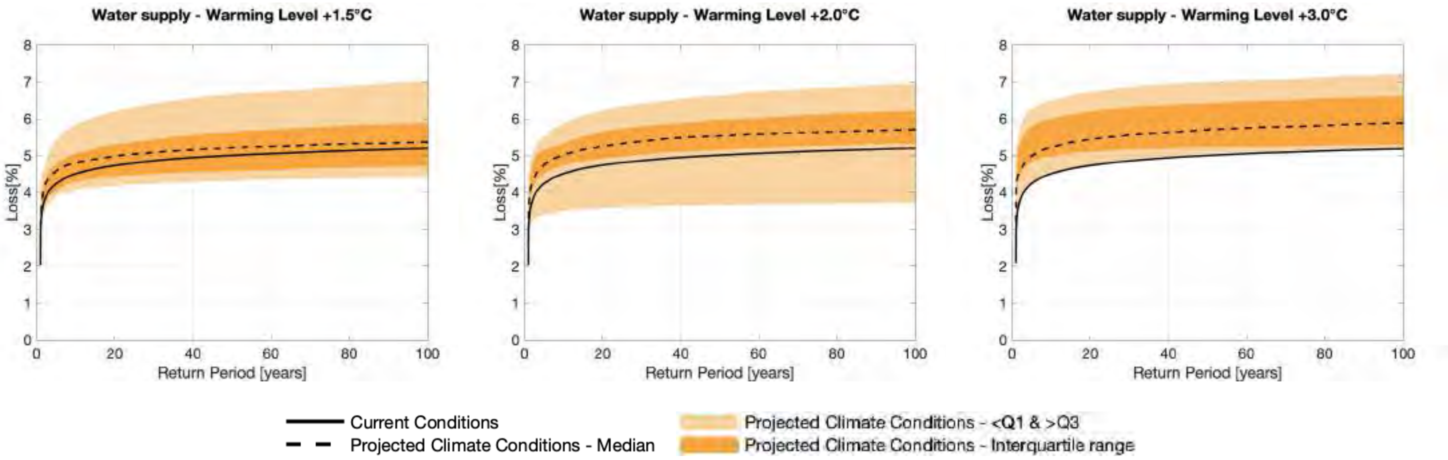


Figure 34:

EU-aggregated PML curves for public water supply under current and projected conditions for +1.5 °C, +2.0 °C, +3.0 °C warming level scenarios. The solid black line is the PML curve for the historical period, while the dotted black line traces out the median of future simulations forced with 11 climate models in both RCP 4.5 and RCP 8.5. The shades of yellow denote the climatic variability of future simulations: dark yellow is the interquartile, while pale yellow represents the lower and upper quarters.

CHAPTER 4

Energy production

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4.1 Key facts

Within European electricity production, nuclear power makes up the largest category accounting for about 22% in 2022. Gas (20%) and coal (16%) are the largest sources of fossil-fuel-based energy production (Eurostat). Among the renewable energy production types, wind (16%) and hydropower (11%) constitute of the largest shares, followed by solar (8%) and biomass (4%) (Eurostat). The European energy system is a major water user, as water is required for hydropower generation, but also for plant cooling in thermoelectric production and for bulk transport (of coal) on major rivers. This makes the system highly susceptible to drought. With drought occurrence expected to increase in frequency and severity in southern Europe as a result of anthropogenic climate change, the European energy system's capacity to produce and provide sufficient energy to meet its demand is further threatened (Van Vliet et al. 2016, Carlino et al. 2021).

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Impact Chain – Energy production

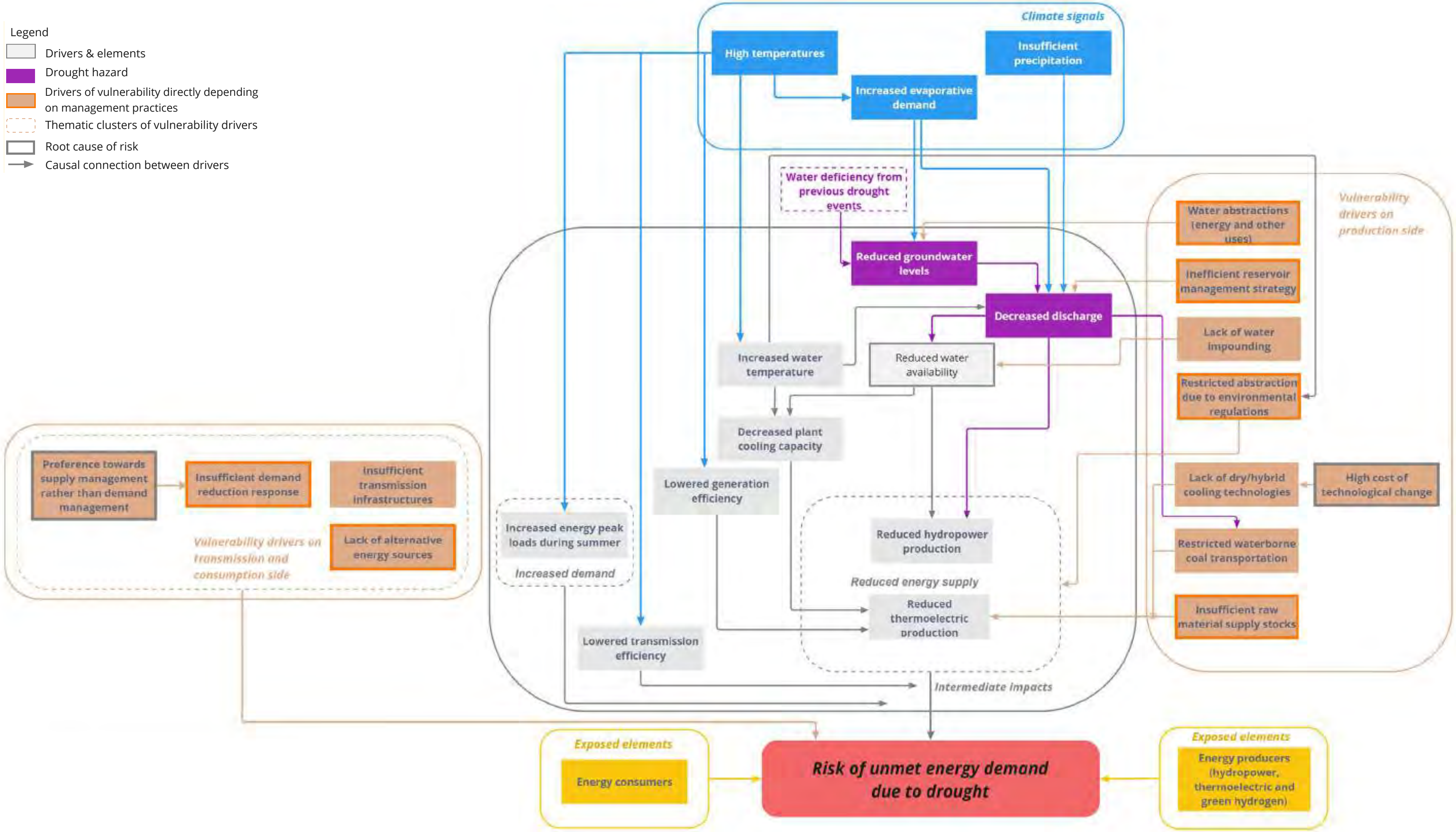


Figure 35: Visual representation of the energy sector impact chain

Risk (energy production)

The European energy system is directly and indirectly dependent on water for energy generation, which makes it highly susceptible to drought events. Here, risk can be defined as the risk of unmet energy demand due to drought, which encompasses both the possibility that water availability is too low, and that demand is too high.

Exposed elements

This risk involves both energy producers and energy consumers. The following types of energy production have been considered here: hydropower and thermoelectric. Thermoelectric covers any energy generated from heat, which itself can come from fossil fuels, the nuclear process, or renewable sources.

Climate signals & Hazards

This risk begins with insufficient precipitation during drought events, which decreases the amount of rainfall runoff and leads to reduced groundwater recharge. Simultaneously, high temperatures are responsible for an increased evaporative demand, increasing evapotranspiration (Van Loon 2015). These processes can lead to reduced groundwater levels, and reduced surface water levels, i.e., in rivers, lakes and reservoirs. Furthermore, these levels might already be negatively affected by water deficiency from previous drought events.

Vulnerability drivers & Intermediate impacts

Numerous vulnerability drivers can contribute to the risk for this system. For example, groundwater and surface waters levels are also affected by water abstractions by other systems, such as agriculture. As a result of the lowered water levels, there might be reduced water availability and decreased discharge, leading to reduced hydropower production (De Stefano et al. 2015). This can be worsened by a lack of water impounding since reservoirs can be used to store water and counter flow variabilities (Siebert et al. 2021). However, reservoirs also pose a management challenge, as inefficient reservoir management may even exacerbate vulnerability to droughts (Ward et al. 2020). At the same time, the reduced surface water levels, particularly when combined with increased water temperatures due to the high atmospheric temperatures, can also lead to reduced thermoelectric production: power plant cooling requires water at an appropriate temperature, and therefore warmer water with a decreased plant cooling capacity may be unsuitable for this purpose (De Stefano et al. 2015).

Moreover, increased water temperature can lead to restricted abstractions due to environmental regulations since the discharge of warmer cooling water back into water bodies may violate the EU Water Framework Directive by harming ecosystems (De Stefano et al. 2015; Carlino et al. 2021). Energy producers that lack dry or hybrid cooling technologies, for instance because of the high costs associated with technological change, are particularly vulnerable. Along this line, reuse of impaired water for cooling can reduce freshwater abstractions and decrease water contamination and abstraction-related impacts on aquatic life and the environment.

Yet another consequence for energy production of reduced surface water levels is that they can lead to restricted waterborne coal transportation due to low flows. This hinders the delivery of the raw material that is needed for thermoelectric production (given the logistical challenges of switching to alternative modes of transportation; Riquelme-Solar et al. 2015): if the producing companies have insufficient raw material supply stocks, they may be forced to reduce their energy production (De Stefano et al. 2015). In addition, high temperatures lead to a lowered generation efficiency of gensets, boilers, and turbines due to of the decreased difference between ambient and combustion temperature (Johnston et al. 2012). The higher temperatures can also lead to lowered transmission efficiency of power lines, as the carrying capacity of electric power cables decreases with the rise in ambient air temperatures (Wenz et al. 2017). These processes can lead to a reduced energy supply, contributing to the risk for this sector. In addition to the above-described processes, there are further vulnerability drivers that can arise regarding energy consumption side. High temperatures are connected to increased energy peak loads during summer because of increased energy use for domestic and industrial cooling (Wenz et al. 2017). If there is an inadequate demand reduction response, for instance due to a lack of sensibilization campaigns and energy reduction policies, the strain on the energy system might become too large. This challenge may be exacerbated if there are insufficient transmission infrastructures to carry energy from other regions in order to compensate for the greater demand. Lastly, a lack of alternative energy sources can increase the system's dependency on sources that are vulnerable to droughts.

4.3 Data-driven model results

4.3.1 Identification of available impact data and exposure

The impact chains identified reductions in energy supply as an important intermediate impact driving the risk of unmet energy demand due to drought. Reductions in energy supply from hydropower and nuclear power (a thermoelectric power) were therefore used in the data-driven analysis. The drought-induced impact on hydropower energy production was evaluated by using the data for monthly hydropower produced per country (NUTS-0 level) provided by the International Energy Agency (IEA) with a limited temporal coverage of 10 years. It is assumed that during prolonged dry periods, hydropower production losses can be expected.

For nuclear power generation, information was gathered from the Power Reactor Information System (PRIS) statistics. This is a database from the International Atomic Energy Agency and monitors in detail the production and outages of individual nuclear plants in associated partner countries. Specifically, the total energy loss in GWh caused by 'Environmental conditions (lack of cooling water due to dry weather, cooling water temperature limits, flood, storm, lightning, etc.) was extracted. It should be noted that the environmental conditions are not limited to dry weather, but also other hazards. The historical records cover the period 2004-2021. Data from single reactors were aggregated to NUTS-2 level, resulting in 35 regions with available data.

Details of input data are reported in Annex II – Energy Production.

4.3.2 Identification of risk drivers

Drought indices related to precipitation, precipitation minus evapotranspiration, and discharge all play a role in driving drought risks related to energy supply (hydropower and nuclear power), with evaporation (SETI) and soil moisture (not shown below) being less significant (Figure 36). The most important indices are all related to the water balance resulting in the available water (after an ideal evapotranspiration process) that makes surface water flow to eventually fill up the reservoirs and serve as cooling water.

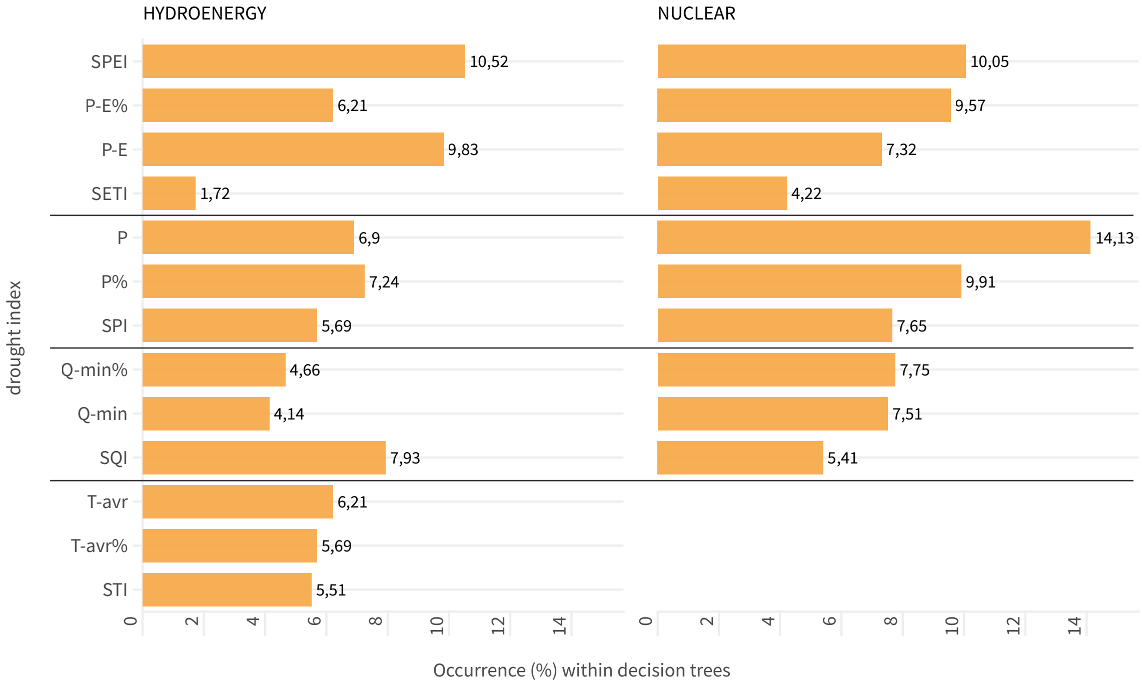


Figure 36:
Occurrence of drought indexes for hydropower and nuclear power in the decision trees.
The group of indices related to Precipitation (P) alone, Precipitation (P) and Evapotranspiration (E) are all relevant for impact prediction on Energy systems (see Annex I for details).

4.3.3 **Drought risk under current climate conditions**

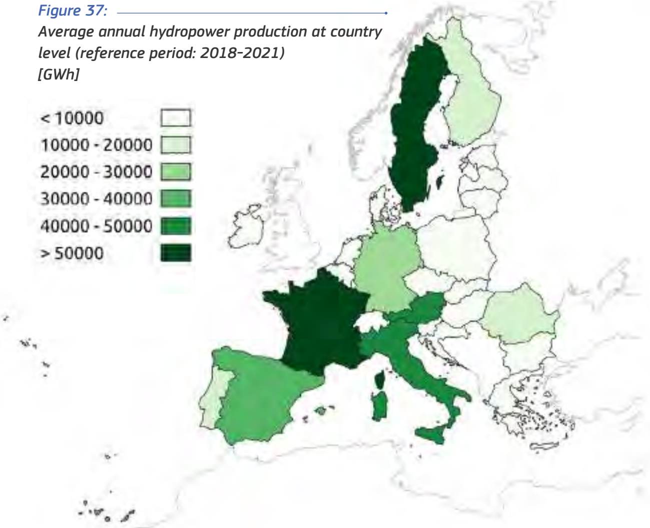
Hydropower

Under current climate conditions, the largest relative reductions in hydropower production due to drought are expected in Portugal, Cyprus, Spain, Greece, Estonia and Bulgaria (Figure 38), although the latter three countries have low exposures and are less at risk in absolute terms. Due to their high exposures, also France and Italy will face substantial risks, although relative losses are smaller.

During extreme events expected to occur on average once every 50 years may also considerably affect northern Europe, with the exceptions of Sweden and Lithuania (Figure 39).

Figure 37:

Average annual hydropower production at country level (reference period: 2018-2021) [GWh]



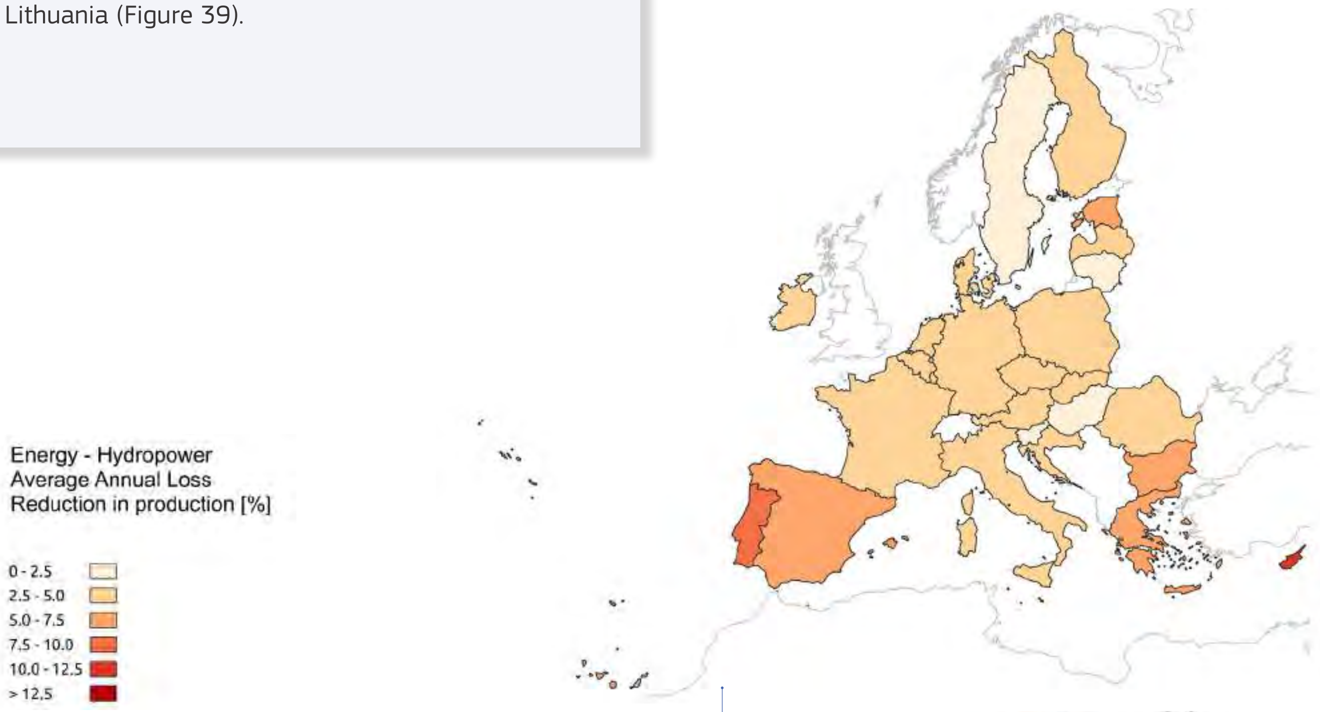
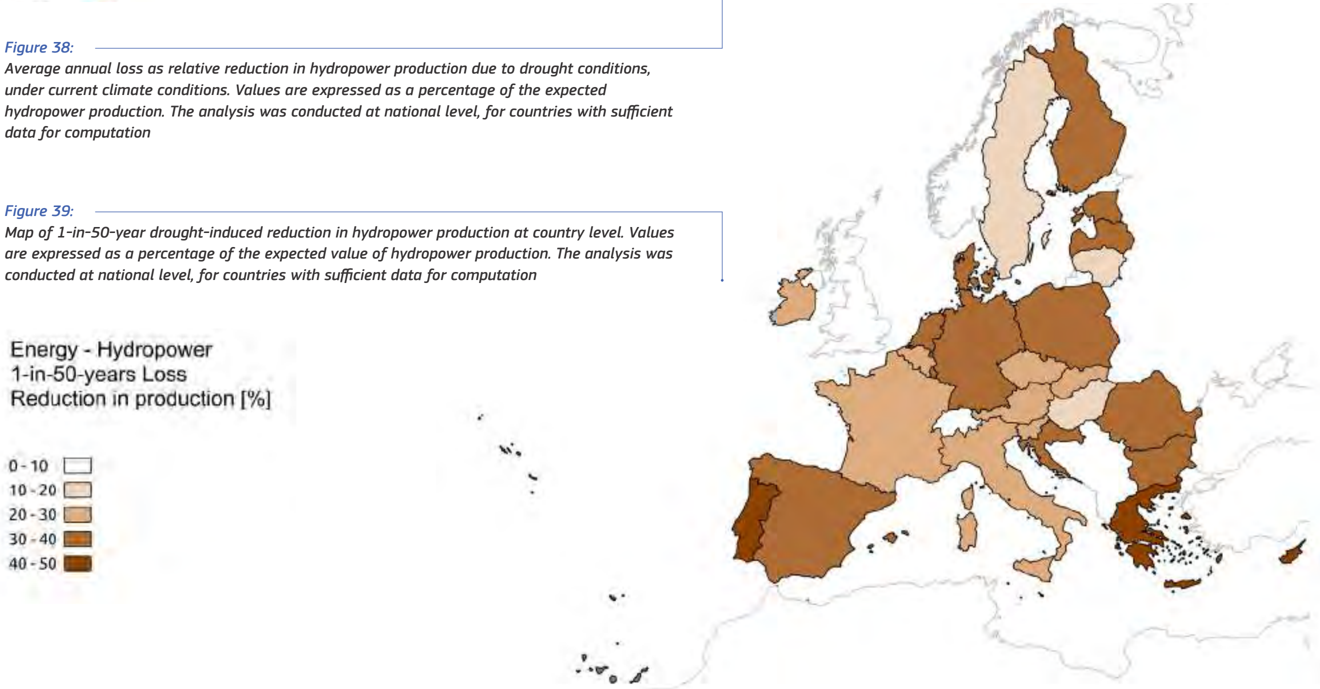


Figure 38:

Average annual loss as relative reduction in hydropower production due to drought conditions, under current climate conditions. Values are expressed as a percentage of the expected hydropower production. The analysis was conducted at national level, for countries with sufficient data for computation

Figure 39:

Map of 1-in-50-year drought-induced reduction in hydropower production at country level. Values are expressed as a percentage of the expected value of hydropower production. The analysis was conducted at national level, for countries with sufficient data for computation



Nuclear power

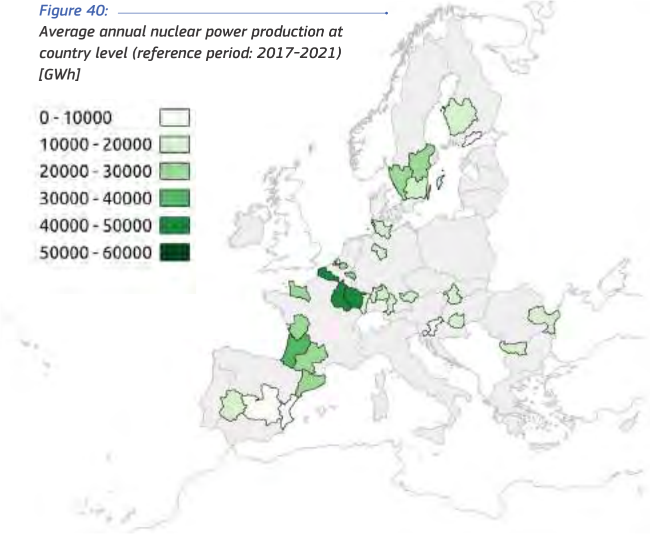
The largest relative reductions in nuclear power production due to drought conditions are currently expected in southern Sweden, western Slovakia, and Spain (Figure 41).

The same spatial risk pattern is seen when considering average annual loss and 1-in-50-year event at NUTS-2 level (Figure 42). Moderate relative losses can have a great impact in France where nuclear power generation has one of the highest nuclear share in the world in the electricity mix (around 68% in 2021, according to Eurostat).

Note that the reduction levels are comparatively small, with average annual losses at about the 1% of the expected production mark, while losses from an extreme event only grow by up to 5%.

Figure 40:

Average annual nuclear power production at country level (reference period: 2017-2021) [GWh]



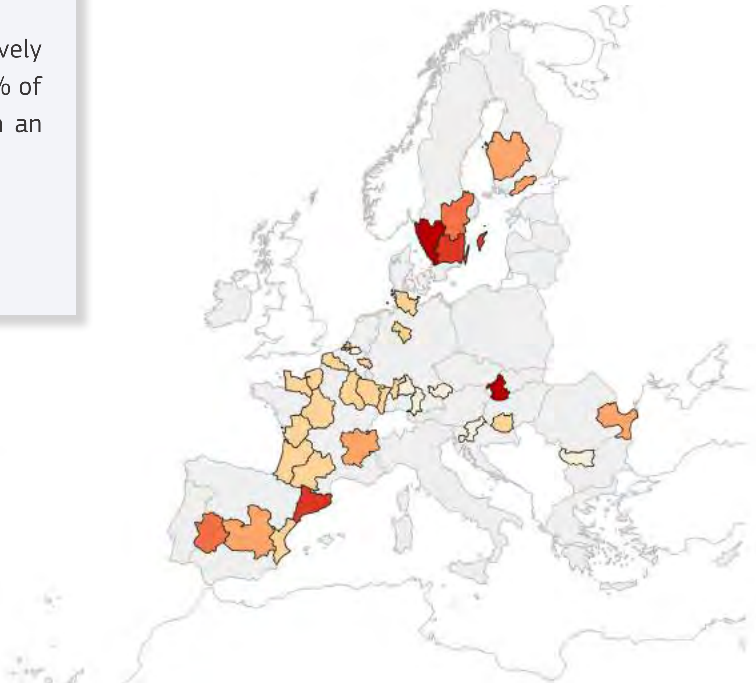
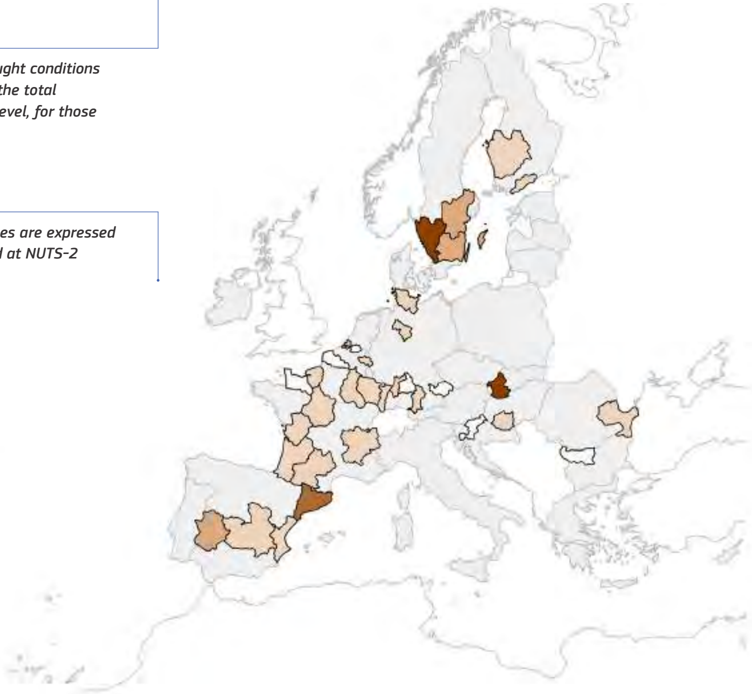


Figure 41:

Average annual loss as relative reduction in nuclear power production due to drought conditions with respect to expected production. Expected annual production is computed as the total produced, plus all outages for each year. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.

Figure 42:

Map of 1-in-50-year drought-induced reduction in nuclear power production. Values are expressed as the percentage of the expected production in year. The analysis was conducted at NUTS-2 level, for those territorial units with sufficient data for computation.



4.3.4 Drought risk under projected climate conditions

Hydropower

The projected changes in hydropower losses due to global warming show very distinct differences between central/ northern Europe and southern Europe. In the Mediterranean region (Spain, Portugal, Greece) hydropower losses at a warming level of +3 °C are projected to double or even triple current losses, while in central and northern Europe, the losses are projected to fall (Figure 43). This is in line with the climate change-induced shifts in streamflow, which constitutes direct inflow for hydropower reservoirs.

The probable maximum loss at lower return periods, at the European scale (Figure 44) is projected to rise with increasing global warming. The signals are less clear, with greater uncertainties, for the rarest events.

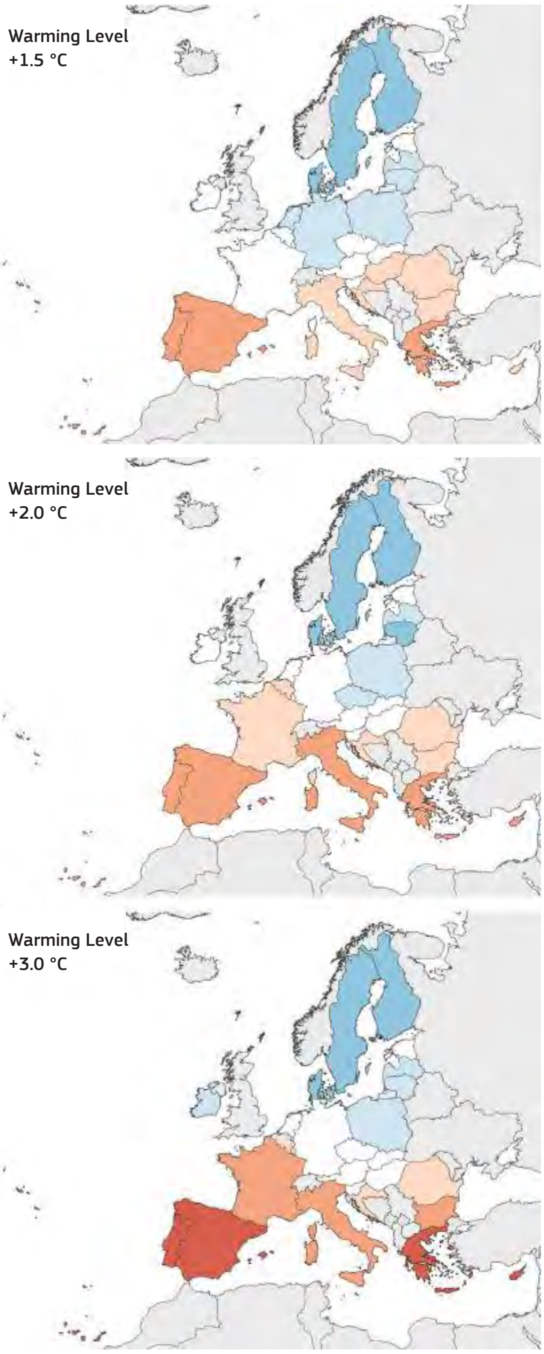


Figure 43:

Variation of drought risk for hydropower production between current and projected climate conditions. Risk Is measured as average annual drought-induced reduction in hydropower production compared to the average expected value under current climate conditions. Results of future simulations forced with 11 climate models in RCP 4.5 and RCP 8.5 are averaged for each warming level (+1.5 °C, +2.0 °C, +3.0 °C). The analysis was conducted at national level, for countries with sufficient data for computation.

Projected Loss / Current Loss

- 🟦 reduction of more than 25%
- 🟦 reduction between 10% and 25%
- ☐ no important variation
- 🟧 increased by a factor of 1.1 to 1.5
- 🟧 increased by a factor of 1.5 to 2
- 🟥 increased by a factor of 2 to 3
- 🟥 increased by a factor of 3 to 4
- 🟥 increased by a factor of more than 4

Probable Maximum Loss (PML) curves

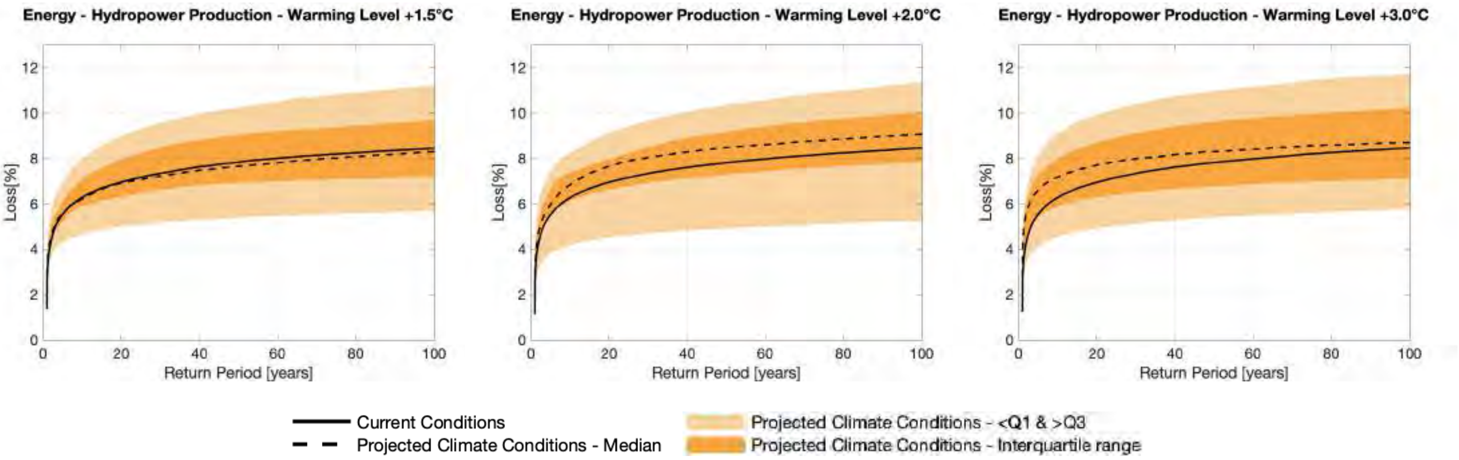


Figure 44:

EU-aggregated PML curves for hydropower production under current and projected conditions for +1.5 °C, +2.0 °C, +3.0 °C warming level scenarios. The solid black line is the PML curve for the historical period, while the dotted black line traces out the median of future simulations forced with 11 climate models in both RCP 4.5 and RCP 8.5. The shades of yellow denote the climatic variability of future simulations: dark yellow is the interquartile, while pale yellow represents the lower and upper quarters.

Nuclear power

Drought-induced losses in nuclear power are projected to increase in all global warming scenarios and across Europe under projected climate conditions. France remains a hotspot, with losses between twice and three times higher than the already high current conditions while current losses are also the highest within the EU. This is in line with the global-warming-induced changes in streamflow regimes (Figure 45).

The PML curves representing the expected at different return periods (Figure 46) show an overall significant increase across warming levels, with a considerable difference in terms of median value between a 2 °C and 3 °C warmer world. Also uncertainty in the path (RCP 4.5 or RCP 8.5 warming) induces large uncertainty regarding the PML values (large spread around median values) in a world warmer by 2 °C or more.

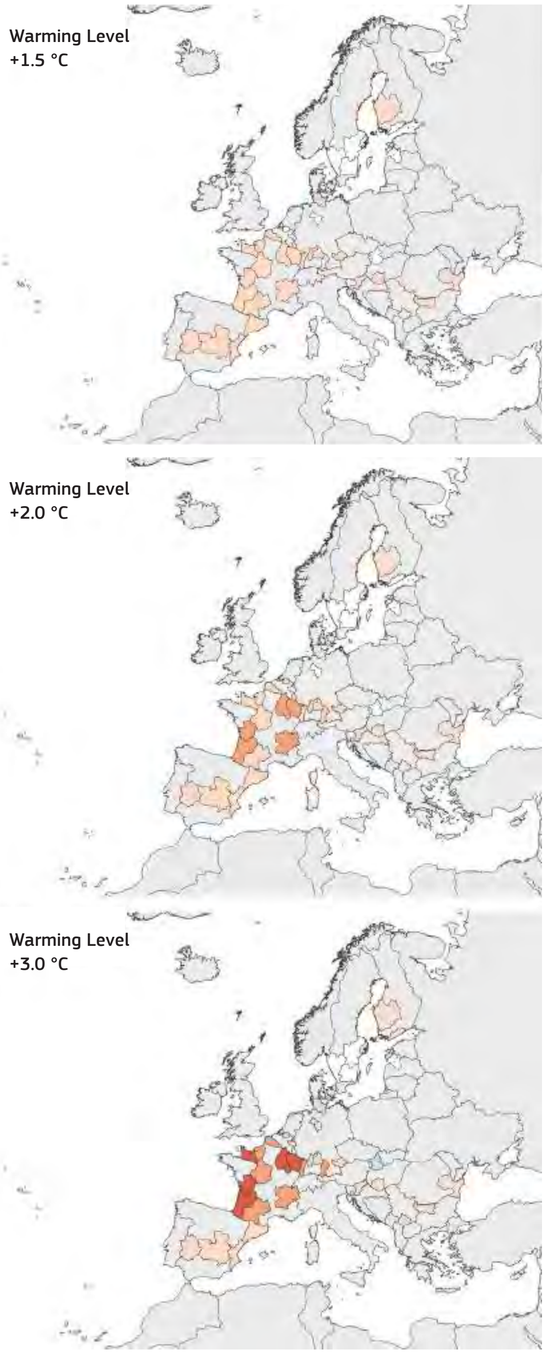


Figure 45:

Variation of drought risk for nuclear power production between current and projected climate conditions. Risk Is measured as average annual drought-induced reduction in hydropower production compared to the average expected value under current climate conditions. Results of future simulations forced with 11 climate models in RCP 4.5 and RCP 8.5 are averaged for each warming level (+1.5 °C, +2.0 °C, +3.0 °C). The analysis was conducted at national level, for countries with sufficient data for computation.

Projected Loss / Current Loss

- 🟦 reduction of more than 25%
- 🟦 reduction between 10% and 25%
- ☐ no important variation
- 🟧 increased by a factor of 1.1 to 1.5
- 🟧 increased by a factor of 1.5 to 2
- 🟥 increased by a factor of 2 to 3
- 🟥 increased by a factor of 3 to 4
- 🟥 increased by a factor of more than 4

Probable Maximum Loss (PML) curves

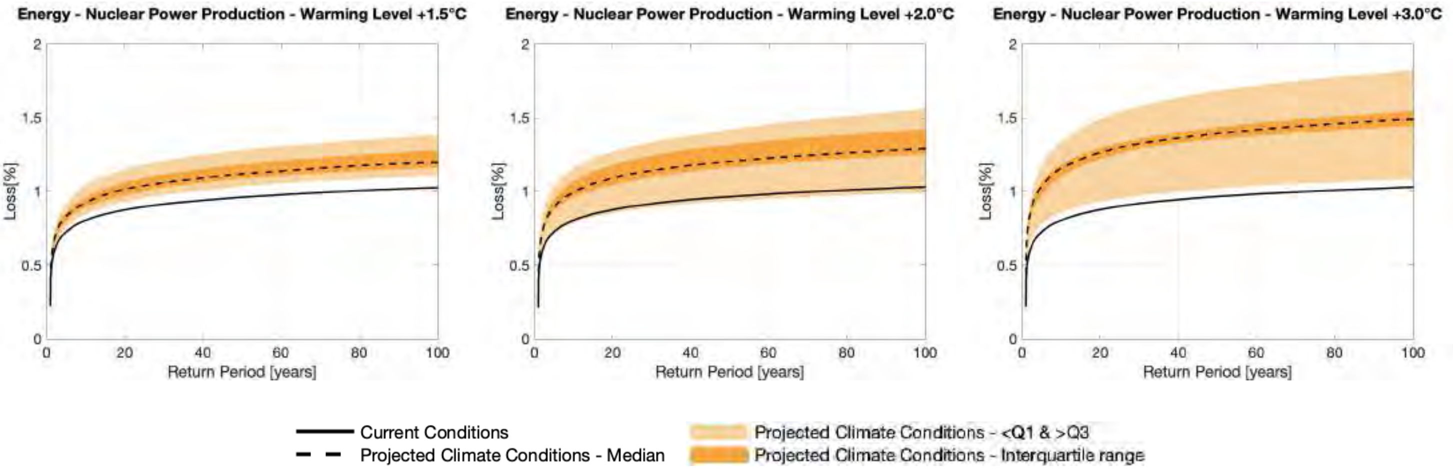
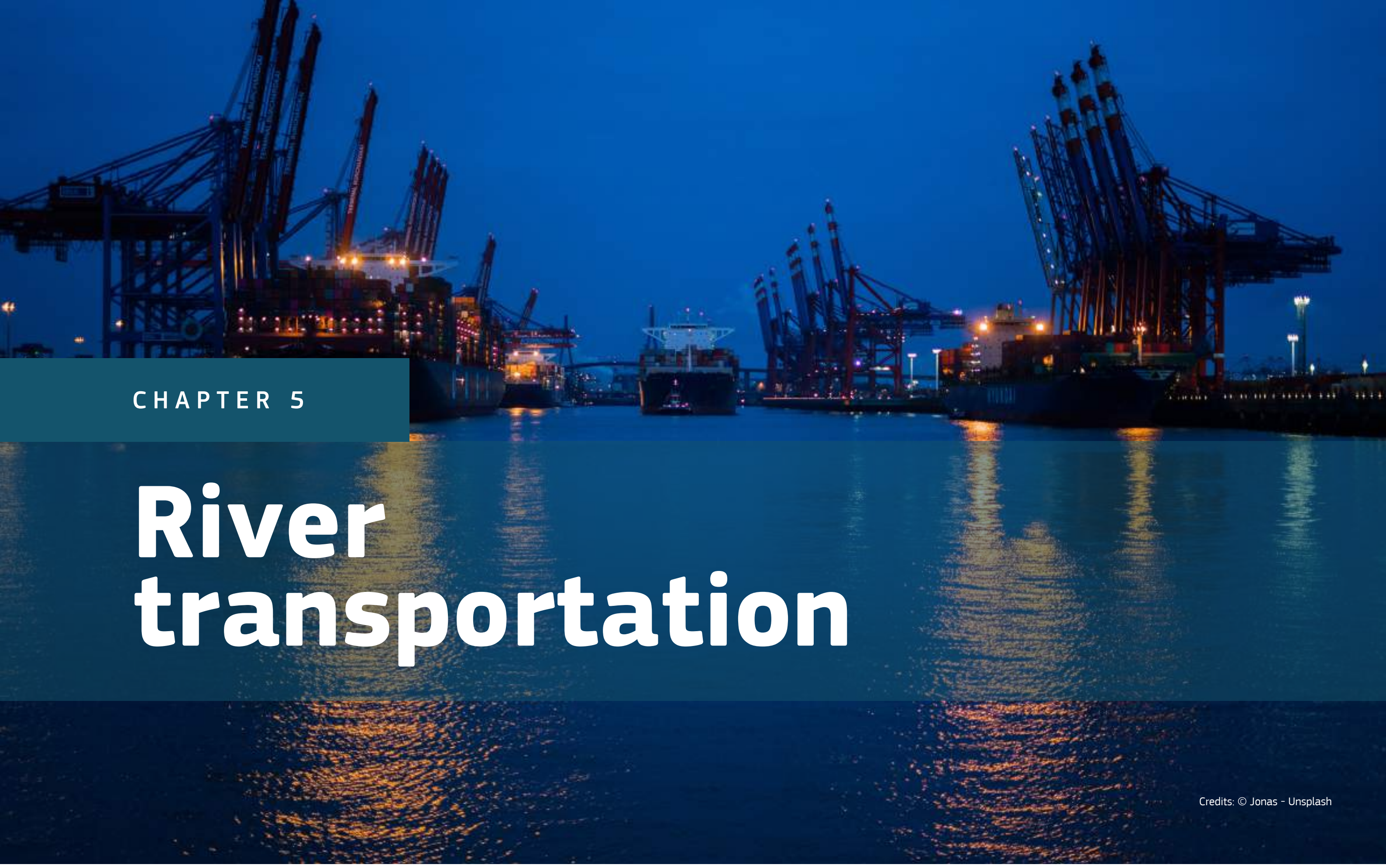


Figure 46:

EU-aggregated PML curves for nuclear power production under current and projected conditions for +1.5 °C, +2.0 °C, +3.0 °C warming levels. The solid black line is the PML curve for the historical period, while the dotted black line traces out the median of future simulations forced with 11 climate models in both RCP 4.5 and RCP 8.5. The shades of yellow denote the climatic variability of future simulations: dark yellow is the interquartile, while pale yellow represents the lower and upper quarters.



CHAPTER 5

River transportation

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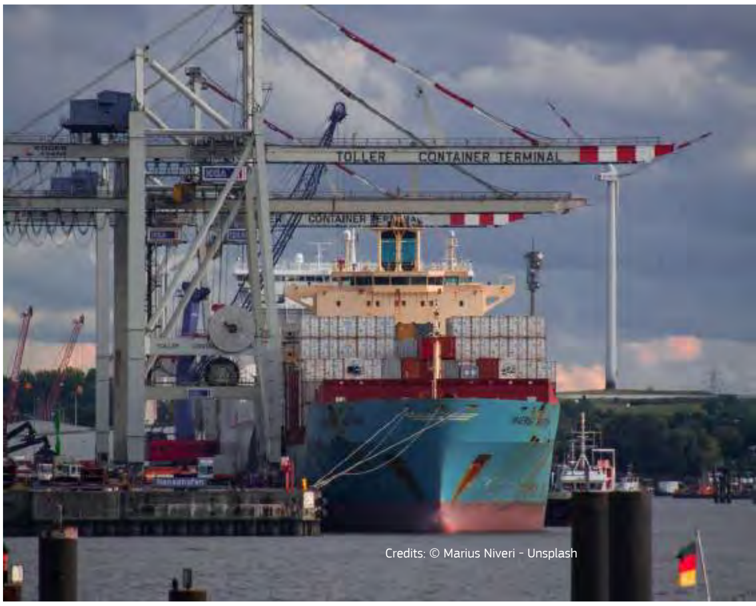
5.1 Key facts

In the last four decades, inland water transport (IWT) in Europe has undergone exponential growth, in terms of traffic and tonnage of transported goods (Notteboom et al. 2007), establishing itself as reliable and high-capacity mode for transporting a variety of goods, including raw materials. IWT in Europe can count on a network of almost 40,000 km of navigable waterways with the majority of these concentrated around relatively few river systems, for instance the Rhine, Danube, Elbe, Rhone, Seine, and Po (Jonkeren et al. 2011) with relatively few opportunities for interconnectivity between them due to the physical constraints of the water channels.

This mode has nonetheless provided unique logistical advantages to connect with the high volumes of commerce mobilized by the global maritime transport system. However, the continued success of river transportation also means that significant portions of the national economies of some European countries are directly or indirectly dependent on this system (including the manufacturing and coal based energy industries), since only a limited and temporary elasticity exists with other transport solutions, e.g. land-based or air-borne (Riquelme-Solar et al. 2015, Wehrle et al. 2022).

Therefore, disruptions of IWT, and consequently along the production chains based on the transported goods can have negative repercussions for the European economy (Ademmer 2023).

Drought events can result in low flow, a condition under which riverine vessels can no longer operate at full capacity due to depth restrictions at bottleneck locations, thus resulting in a temporary interruption of the supply chain for industries dependent on IWT. The droughts of 2018 and 2022, for example, had severe consequences for commercial navigation on multiple European waterways, causing temporary disruptions to the delivery of bulk and container goods (Ademmer et al. 2020).



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Impact Chain – River transportation

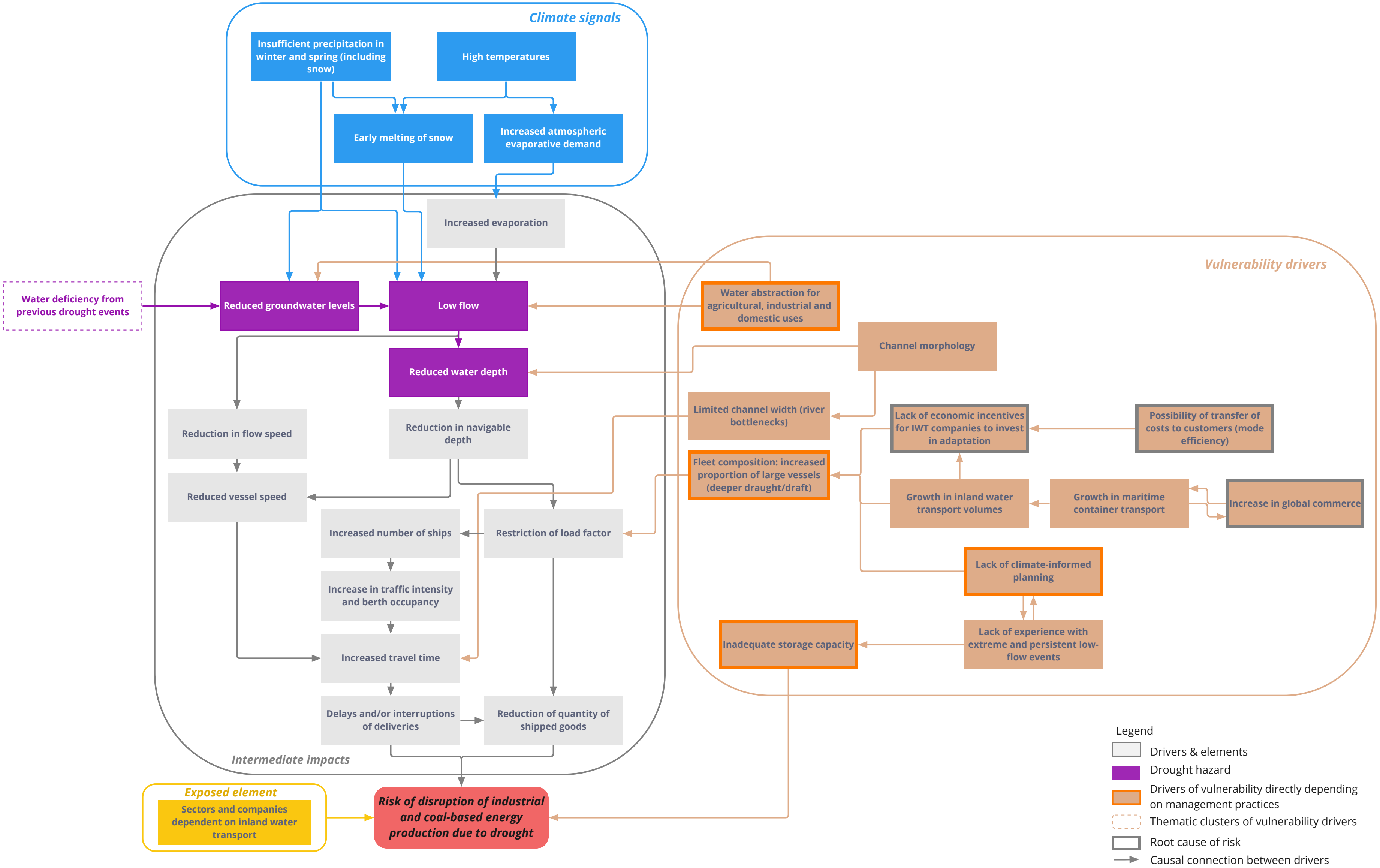

Figure 47: Visual representation of the river transportation impact chain

Risk (river transportation)

Drought events can result in low flow, preventing river-borne vessels from operating at full capacity, and resulting in a temporary supply chain interruption affecting the industries dependent on IWT. For this reason, the risk selected for this system is the risk of drought-induced disruption of industrial production and coal-based energy generation.

Exposed elements

River traffic is managed by specialised transport companies. While low flow events can disrupt these companies' operations, the costs are generally passed on from the navigation companies to their customers through an increase in price per tonne transported (Jonkeren et al. 2013). Therefore, the sectors and companies dependent on IWT are those most likely to suffer economically from low-flow events. This comprises a variety of critical industries, since it does not only affect transportation of industrial goods but also of raw materials such as coal, metal ores and refined petroleum products (ibidem). Moreover, interrupting the supply chain for these goods can significantly disrupt industrial production and indirectly affects economic sectors and segments of society well beyond the geographical extent of the river areas.

Climate signals & Hazards

The main navigable rivers in Europe are primarily characterised by nival, glacial and mixed hydrological regimes, while also being strongly pluvial in the downstream sections. Thus, insufficient precipitation in winter and spring may result in low flow and can pose a hazard for this system. Low flow can also be the result of reduced groundwater levels related to insufficient precipitation and water deficiency from previous drought events. To a minor extent, increased evaporation derived from the increase in atmospheric water demand caused by high temperatures, can also contribute to low flow. The latter also plays an important role in the early melting of snow, which reduces the water availability especially for the spring and summer months (International Commission for the Protection of the Rhine 2020). Because of low flows, the water depth available to vessels is reduced, limiting navigability.

Vulnerability drivers & Intermediate impacts

The abovementioned reduced groundwater levels can also potentially be connected to excessive water abstraction for agricultural, industrial and domestic uses. Further drivers of vulnerability for IWT include physical constraints to navigation, such as channel morphology, which directly influences the water depth available for navigation in the river (Vinke et al. 2022). Because of the reduced navigable depth during low flow events, vessels need to decrease their draught by restricting their load factor (Jonkeren et al. 2013; Riquelme-Solar et al. 2015). This has become a more frequently necessary measure, also due to a greater proportion of large vessels in fleet composition over recent decades. This evolution in vessel size is connected to the increase in global commerce (Bishop et al. 2011) and the resulting growth in maritime container transport (Notteboom 2007; Button and Pels 2010), which has driven the growth of inland water transport volumes (Vinke et al. 2022). Having to restrict the load in each ship, transport companies may respond by mobilising a higher number of vessels to ensure transportation of the same total load. This can result in an increase in the number of ships operating, therefore increasing traffic intensity and berth occupancy, necessary for the loading and unloading operations (Vinke et al. 2022). In addition, this can prompt an increase in travel time (Christodoulou et al. 2020), caused by the slower vessel speed due to the reduced flow speed of the water (Riquelme-Solar et al.,2015) as well as longer waiting times at locks, which can lead to delays and/or interruption in deliveries, along with an overall reduction in quantity of shipped goods. For some industries, this may have significant repercussions for their supply chain: in most cases, a disruption longer than seven days can be considered as problematic (Riquelme-Solar et al. 2015). The IWT sector has recently seen disruptive climatic events in Europe, such as the 2018 (International Commission for the Protection of the Rhine 2020) and the 2022 low flows. Because of the relative stability experienced over multiple decades, the transport sector, so far, has not considered climate change in its planning (Jonkeren et al. 2013). Moreover, the efficiency of this transport mode has created inelasticity with other modes of transportation, which enables the transfer of costs from the transport companies to the customers, as alternative transportation remains exceedingly expensive, especially for bulk goods, such as coal (Jonkeren et al. 2011; Riquelme-Solar et al. 2015). These conditions have generated a general lack of economic incentives for IWT companies to invest in adapting to the changing climate (Riquelme-Solar et al. 2015), i.e., considering fleets with more ships of reduced draught (Jonkeren et al. 2013). The lack of experience with extreme and persistent low-flow events also affects the dependent industries since most do not plan for a storage capacity capable of overcoming long or frequent disruptions (Riquelme-Solar et al. 2015).

5.3 Data-driven model results

5.3.1 Identification of available impact data

The drought-induced impact on inland water transportation was evaluated by using “transported goods” from the Eurostat “Transport by nationality of vessel” dataset[1], which was identified in the impact chain as a key factor in the risk of disruption of crucial industrial activities. This dataset contains data in the unit of 1,000 tonnes of carried goods on a quarterly scale from 1982 through to 2022 (with data gaps) reported at the NUTS-0 level (countries). Given the limited amount and inconsistency of data in the early period, only data from the year 2000 onwards was used.

In this analysis, we focused on inland waterways with significant shipping traffic. These include the rivers Elbe, Meuse, Seine, Vistula, Rhine, and Danube, and their connected canals. This analysis therefore centred on the countries of Germany, the Netherlands, Belgium, France, Poland, Austria, Croatia, Hungary, Slovakia and Romania. Of these rivers (and countries), the Rhine and Meuse are among the most used inland waterways, resulting in high exposure in the Netherlands, Germany and Belgium.

Details of input data are reported in Annex II – River Transportation.

5.3.2 Identification of risk drivers

For river transportation, the analysis was conducted using only streamflow-derived indices, given the evident relationship between minimum discharge and the navigability of rivers and canals.
As only streamflow indices are used, we can focus on more detail of the indices. Figure 48 shows the occurrence of SQI with different accumulations, minimum monthly value over the year and duration of SQI below a certain threshold (SQI-1dur, SQI-3dur, etc.). As would logically be expected, SQI-1 is the most common index in the decision trees as this represents river flow at a particular moment.

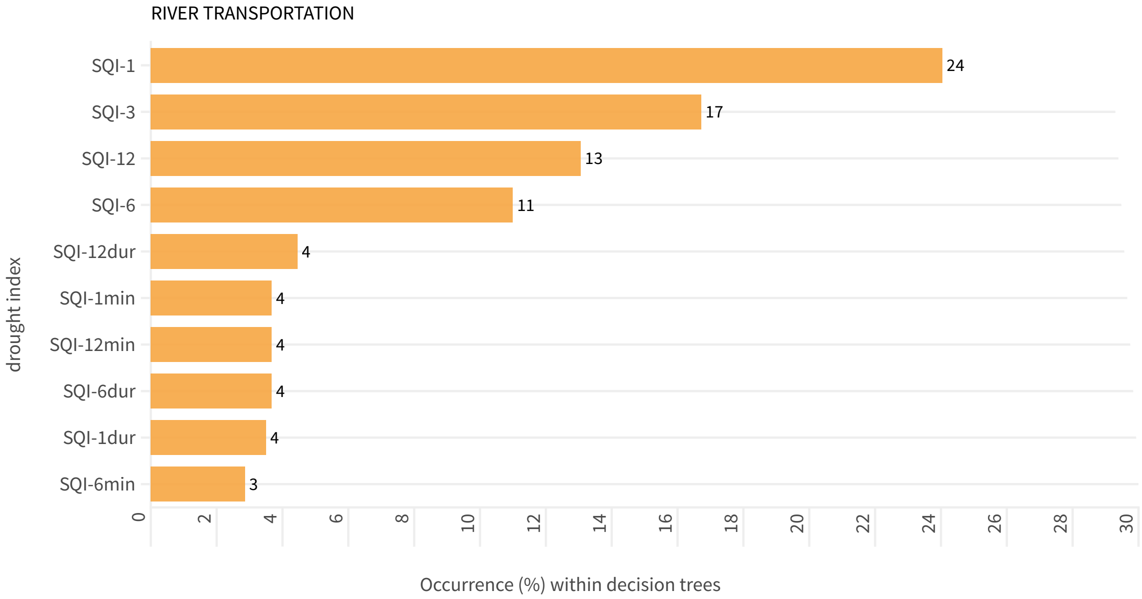

Figure 48:
Occurrence of drought indexes in the decision trees for transport.
Among the discharge-related indexes the most relevant duration for river transportation impact prediction is one month.

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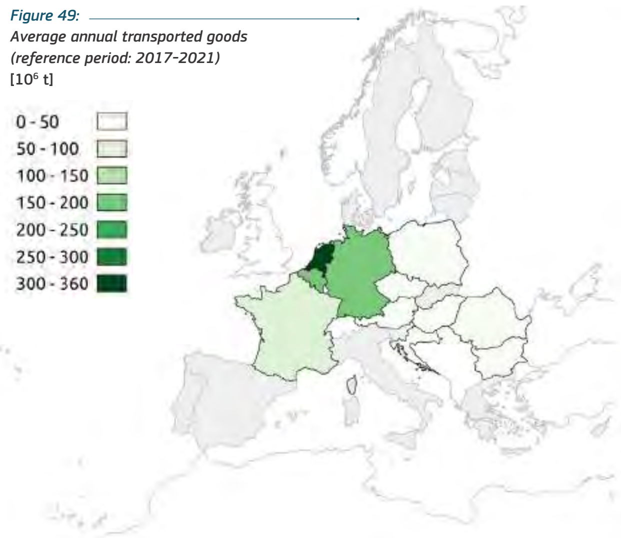
[1] *https://ec.europa.eu/eurostat/databrowser/product/page/iww_go_qnave*

5.3.3 **Drought risk under current climate conditions**

Results of the risk analysis under current climate conditions are shown in terms of average annual loss as well as in the loss to be expected on average once every 50 years, whereby loss is the relative reduction in transported goods (percentage reduction compared to the expected tonnes of goods transported for each country per year).

The average annual loss (AAL) of transported goods in relation to expected transportation is quite homogeneous in the countries considered: less than 2.5% with the exception of Poland and Croatia which experience AAL of 2.5-5%, (Figure 50). This is to be expected given that these countries are linked with the same rivers, and bottlenecks in these rivers will affect all riparian countries. When considering extreme impact events, eastern Europe seems to suffer more from extreme (1-in-50-year) events, which is probably related to the smaller river basins with less storage to supply base flow (Figure 51). Note that due to the large exposure, the absolute losses in the Rhine-Meuse area are estimated being substantial, even with low percentages (Figure 49).

Figure 49:
Average annual transported goods (reference period: 2017-2021)
[10^6 t]



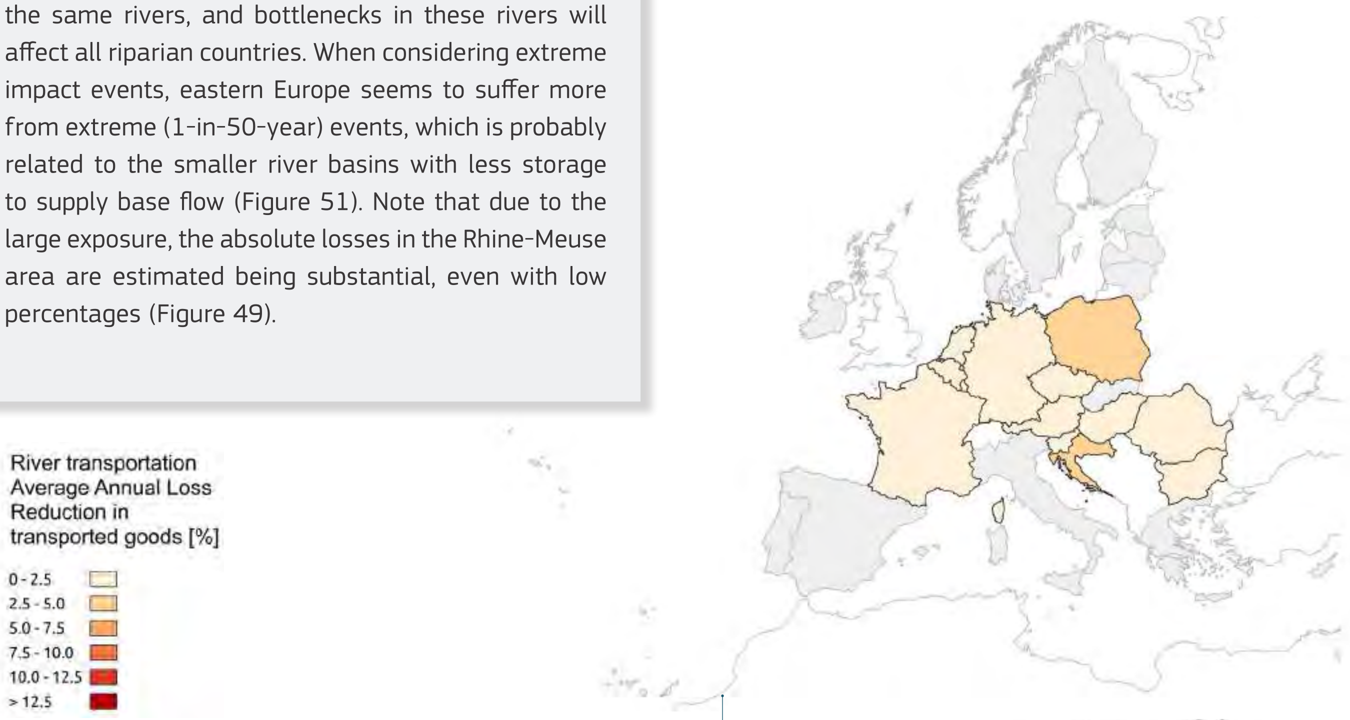


Figure 50:
Average annual relative reduction in transported goods due to droughts, as percentage of the average expected tonnes transported. The analysis was conducted at national level, for countries with sufficient data for computation.

Figure 51:
Map of the maximum relative reduction in transported goods to be expected on averages 1-in-50-years. Values are expressed as a percentage of the average expected tonnes transported. The analysis was conducted at national level, for countries with sufficient data for computation.

5.3.4 **Drought risk under projected climate conditions**

Under projected climate conditions, the relative risk for Germany, Belgium and the Netherlands decreases somewhat, but due to the high level of transported goods in Rhine-Meuse area, these three countries will remain the most affected. However, in relative terms (Figure 52) drought conditions under global warming are projected to progressively worsen for the Danube, especially in the upper part, probably due to a decrease in snow melt, while the lower section receives a contribution from tributaries, where precipitation increase compensates for the upstream reduction in discharge. The reduction in average drought-induced losses in Germany and the Rhine catchment basin is in line with an expected increase in overall precipitation (Christodoulou et al. 2020). At European scale, the PML curves increase sharply together with uncertainty for higher return periods (Figure 53). Little to no difference in loss compared to to current conditions was found for France. France is expected to experience discharge decreases in the south of the country, but these may be compensated by an increase in discharge in the northern catchments basins and/or may not influence rivers that contribute most to the national amount of transported goods. It should be noted that there may be non-linearities associated particularly with melt-driven streamflow, as this could increase streamflow under low warming levels, but may reverse in the event of the snowpacks at high altitude starting to disappear. Overall, the impact of climate change on inland navigation remains hard to predict with the currently available data, and is subject to large uncertainties (Vinke et al. 2022).

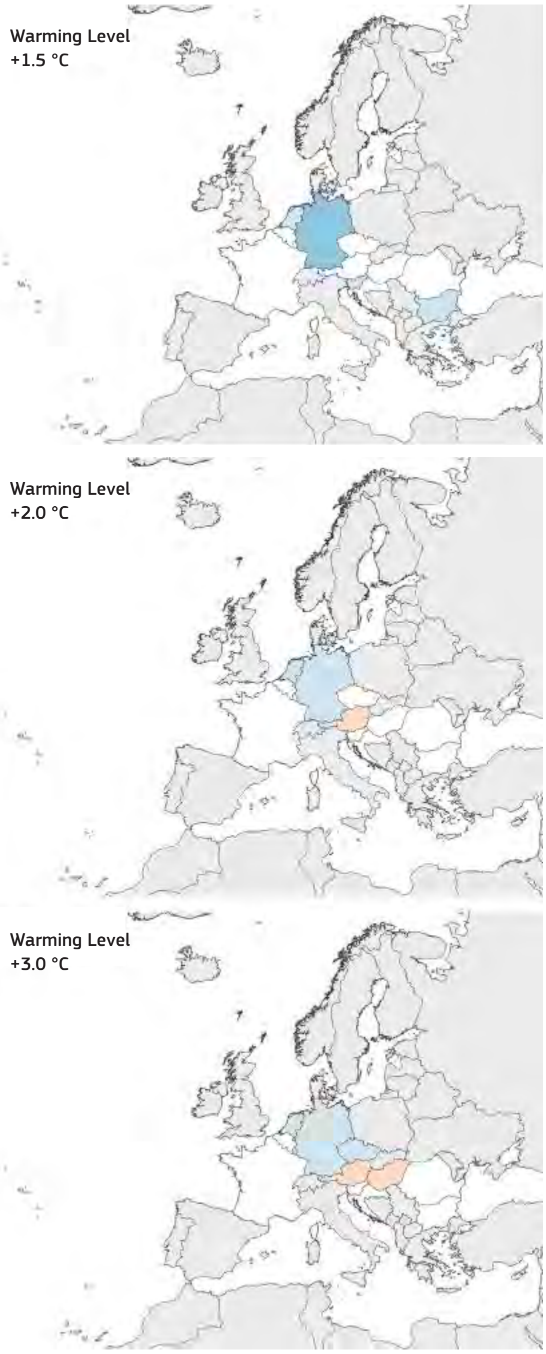


Figure 52:
Variation in drought risk for river transportation between current and projected climate conditions. Risk is measured as average annual reduction in transported good compared to the average expected value under current climate conditions. Results of future simulations forced with 11 climate models in RCP 4.5 and RCP 8.5 are averaged for each warming level (+1.5 °C, +2.0 °C, +3.0 °C). The analysis was conducted at national level, for countries with sufficient data for computation.

Projected Loss / Current Loss

- 🟦 reduction of more than 25%
- 🟦 reduction between 10% and 25%
- ⬜ no important variation
- 🟧 increased by a factor of 1.1 to 1.5
- 🟧 increased by a factor of 1.5 to 2
- 🟥 increased by a factor of 2 to 3
- 🟥 increased by a factor of 3 to 4
- 🟥 increased by a factor of more than 4

Probable Maximum Loss (PML) curves

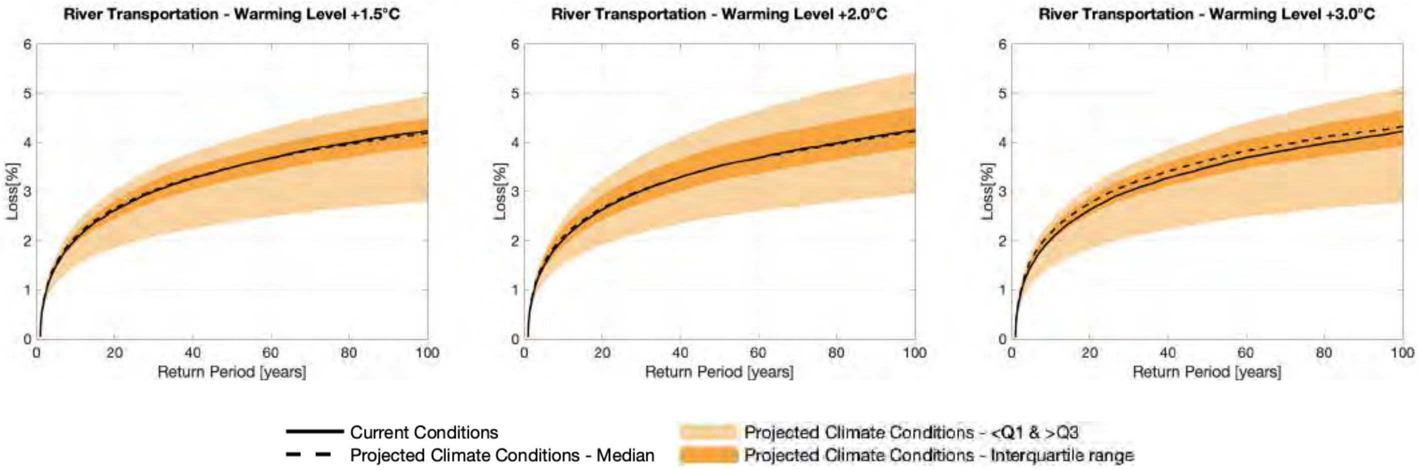


Figure 53:
EU-aggregated PML curves for river transportation under current and projected conditions for +1.5 °C, +2.0 °C, +3.0 °C warming level scenarios. The solid black line is the PML curve for the historical period, while the dotted black line traces out the median of future simulations forced with 11 climate models in both RCP 4.5 and RCP 8.5. The shades of yellow denote the climatic variability of future simulations: dark yellow is the interquartile, while pale yellow represents the lower and upper quarters.

CHAPTER 6

Terrestrial and freshwater ecosystems

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6.1 **Key facts**

Terrestrial ecosystems

In this atlas we focus on European forests, predominantly classified as semi-natural, with only a small percentage of them being plantations or undisturbed forests. Forests in Europe are important providers of ecosystem services, including those supporting the forestry sector, which plays a relevant part in the economy of many European countries (UNECE, FAO 2020). European forest ecosystems are increasingly faced with extreme drought events (Gazol et al. 2022), resulting in high levels of tree stress and mortality (Senf et al. 2020, George et al. 2021).

Freshwater ecosystem

According to the Global Ecosystem Typology adopted by the International Union for the Conservation of Nature (Keith et al. 2020), all permanent and temporary freshwater bodies, as well as saline water bodies not directly connected to the oceans, fall within the freshwater realm. As part of the EDORA project, we focused on rivers, lakes, and freshwater wetland ecosystems, all of which provide ecosystem services that are important at the continental level and that help fulfil the EU's Water Framework Directive (Acreman et al. 2007). Some of these ecosystem services include water purification and provisioning, habitats for aquatic species, flood protection and recreation (Grizzetti et al. 2016. At the same time, freshwater ecosystems are highly vulnerable to stressors, including climatic changes and water scarcity (Arenas et al. 2016, Kristensen et al. 2018). The exposure of freshwater ecosystems to stressors can cause non-linear, rapid transitions between ecosystem states, with undesired regime shifts as the worst-case scenario.

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Impact Chain – Terrestrial ecosystems

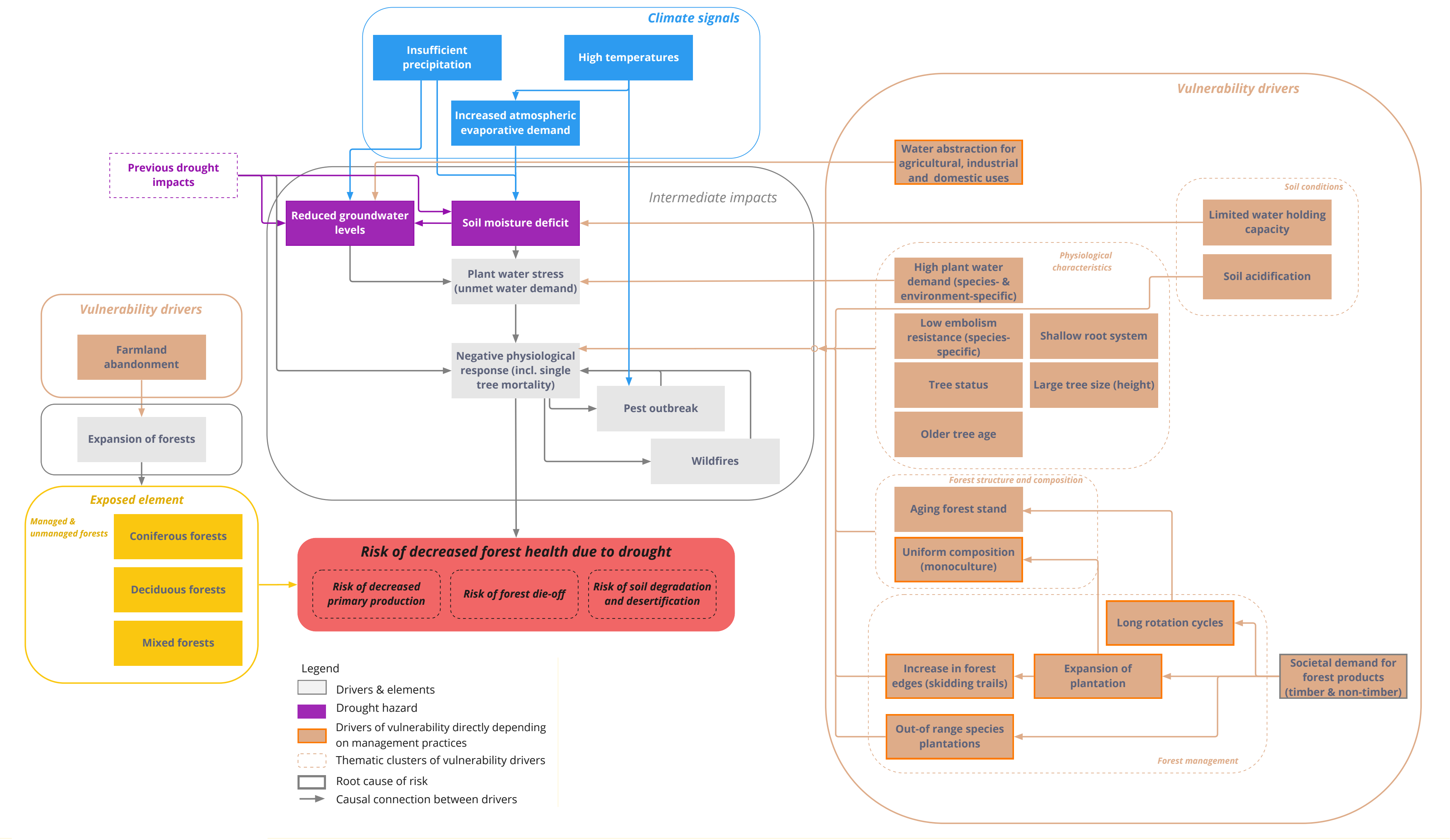


Figure 54: Visual representation of the forest ecosystems impact chain

Risk (forest ecosystems)

Droughts can have a variety of impacts on forest ecosystems, affecting their composition, structure, and functions. In this context, the overarching risk for this system is identified as risk of decreased forest health due to drought. This can encompass a multitude of possible impacts, among which decreased primary production, forest die-off (as a result of tree mortality), and soil degradation and desertification.

Exposed elements

Different types of forests are exposed to these risks. In Europe, more than 90% of forests are semi-natural, i.e., at least partially managed (including plantations), while only a small amount remains unmanaged (Forest Europe, 2020). In addition, European forests are predominantly coniferous or deciduous, with only 17% mixed (Forest Europe 2020), with various ratios of species, and both types experiencing increased mortality rates (Buras and Menzel 2018). The amount of forested area exposed to drought risks has increased in Europe also because forests have undergone important spatial expansion in recent decades (Palmero-Iniesta et al. 2021), mainly due to the extensive abandonment of farmland that has occurred throughout most of the continent (Terres et al. 2015).

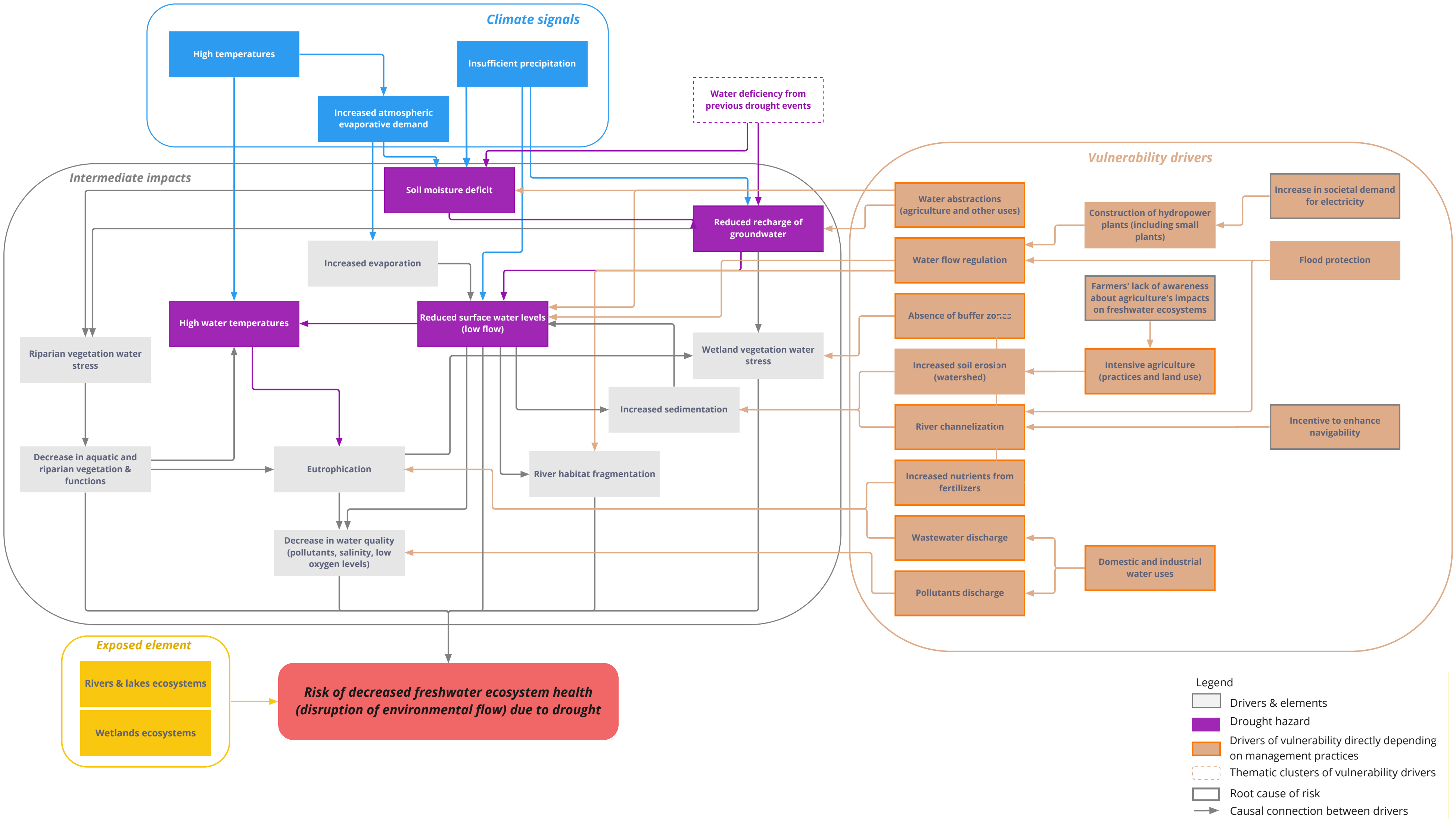
Climate signals & Hazards

The climatic trigger to these risks is increasingly understood to be the combination of insufficient precipitation and high temperatures. The latter element has acquired particular relevance in recent years, since it is recognised as creating stressful conditions (such as increased atmospheric evaporative demand) that worsen the effect of insufficient precipitation (Neumann et al. 2017; Albert et al. 2018; Hammond et al. 2022). These signals can translate into actual hazards for the exposed trees in terms of soil moisture deficit, which also contributes to reduced groundwater levels. In addition, trees can exhibit severe impacts because of the "carry-over" effect of previous drought impacts (George et al. 2021).

Vulnerability drivers & Intermediate impacts

Various vulnerability factors can exacerbate the hazard conditions: for example, extensive water abstraction for agricultural, industrial, and domestic uses can significantly diminish the groundwater available to the forest ecosystem. Soil moisture levels are also dependent on soil conditions (Rehschuh et al. 2017), such as water holding capacity (Schuldt et al. 2020). When their water demand is not met, plants can suffer intense water stress, triggering a negative physiological response at the level of single trees, or entire forest stands. The level of stress is dependent on the physiological characteristics of the plants (Crausbay et al. 2017): species with high water demand will be more affected (Rehschuh et al. 2017). Stress can also be exacerbated by soil acidification (Altman et al. 2017) and by the presence of shallow root systems (Lindh et al., 2014; Phillips et al., 2016) with low embolism resistance (Choat et al. 2012). In addition, tree size (Bennett et al. 2015; Grote et al. 2016; Taccoen et al. 2021), age (Zang et al. 2014; Lucas-Borja et al. 2021; Bréda and Brunette 2019) and status (Grote et al., 2016; Taccoen et al. 2021), i.e., dominant vs suppressed, can contribute to an increased level of tree vulnerability. However, these tree characteristics can also present non-linear responses to water stress (Trugman et al. 2021; Neumann et al. 2017), for instance only manifesting when certain thresholds are crossed. Forest structure and composition also contribute to the impacts of drought: forests with more uniform composition – which stems from a demand-driven expansion of plantation (McEwan et al. 2020), are generally considered to be more vulnerable (Pukkala 2018). Moreover, under specific conditions, forest management practices can also directly and indirectly exacerbate vulnerability. Societal demand for timber and non-timber forest products, which has stabilised but continues to be elevated (McEwan et al. 2020; Forest Europe 2020), can drive practices such as long rotation cycles (Bréda and Brunette 2019), and out-of-range forest composition. These, in turn, may increase the ecosystem's vulnerability, especially under climate change conditions (Bastrup-Birk 2016). In some cases, impacts can also relate to intensive forest exploitation, which can result in an increase in forest edges, and alter the capacity for microclimate regulation (Blumröder et al. 2021). The impacts of droughts on forest ecosystems can be heavily compounded by related and cascading impacts and hazards for which drought events create particularly suitable conditions, such as pest outbreaks (Hlásny et al. 2021; Schuldt et al. 2020; Jactel et al. 2019; Trugman et al. 2021) and wildfires (Bastrup-Birk 2016). This can lead to a feedback loop in which the negative physiological response of single trees, including single tree mortality, increases the vulnerability of forest ecosystems altogether.

Impact Chain – Freshwater ecosystems



Climate signals

High temperatures

Insufficient precipitation

Increased atmospheric evaporative demand

Water deficiency from previous drought events

Intermediate impacts

Soil moisture deficit

Reduced recharge of groundwater

Increased evaporation

High water temperatures

Reduced surface water levels (low flow)

Riparian vegetation water stress

Wetland vegetation water stress

Increased sedimentation

Decrease in aquatic and riparian vegetation & functions

Eutrophication

River habitat fragmentation

Decrease in water quality (pollutants, salinity, low oxygen levels)

Vulnerability drivers

Water abstractions (agriculture and other uses)

Construction of hydropower plants (including small plants)

Increase in societal demand for electricity

Water flow regulation

Flood protection

Absence of buffer zones

Farmers' lack of awareness about agriculture's impacts on freshwater ecosystems

Increased soil erosion (watershed)

Intensive agriculture (practices and land use)

River channelization

Incentive to enhance navigability

Increased nutrients from fertilizers

Wastewater discharge

Domestic and industrial water uses

Pollutants discharge

Exposed element

Rivers & lakes ecosystems

Wetlands ecosystems

Risk of decreased freshwater ecosystem health (disruption of environmental flow) due to drought

Legend

⬜ Drivers & elements

🟪 Drought hazard

🟧 Drivers of vulnerability directly depending on management practices

⬚ Thematic clusters of vulnerability drivers

▭ Root cause of risk

→ Causal connection between drivers

Figure 55: *Visual representation of the freshwater ecosystems impact chain*

Risk (freshawater ecosystems)

The concept of environmental flow, which indicates the quantity, timing, and quality of water flows' necessary to maintain the ecosystem's functions (Poff et al. 2010; Yeakley et al. 2016; Schmutz and Sendzimir 2018; Kuriqi et al. 2020), is useful in identifying the risks posed by droughts for freshwater ecosystems. Alteration of the environmental flow's critical threshold results in a loss of balance and functions in the ecosystems, and a consequent reduction in their ecosystem services. For this reason, this conceptual model focuses on the risk of decreased freshwater ecosystem health, described as a disruption of the required environmental flow.

Exposed elements

Rivers and lakes host a variety of ecologically complex ecosystems, whose composition and functions vary in size and location. They form a complex interaction with their surrounding environment, including riparian zones, which are important regulators of water courses' health (Singh et al., 2021). Terrestrial wetlands dependent on freshwater are also likely to suffer negative impacts from drought events (Hering et al. 2010).

Climate signals & Hazards

Insufficient precipitation is a direct driver of drought impacts, as freshwater ecosystems receive water influx from runoff and throughfall (Lake 2011). Since many European rivers are characterised by glacial, nival and mixed regimes, precipitation includes winter precipitation in the form of snow, which can influence drought conditions from springtime onwards. Insufficient precipitation may result in reduced surface water levels. High temperatures are an additional climate factor that can negatively impact freshwater ecosystems: higher temperatures increase the atmospheric evaporative demand, which results in increased evaporation (thus contributing to low flow, especially in lentic systems) and contributes to soil moisture deficit conditions affecting the neighbouring riparian ecosystems. Additionally, high temperatures can combine with reduced water levels to create high water temperatures in water bodies, thus noticeably altering the ecological balance (Mosley 2015; Jeppesen et al. 2015; Bond et al. 2008). Recharge from groundwater is also an important element for many freshwater ecosystems, such as wetlands (Wossenyeleh et al. 2021) and riparian ecosystems (Stella and Bendix 2019): Therefore, soil moisture deficit, reduced recharge of groundwater, determined by insufficient precipitation and water deficiency from previous drought events are considered as hazards.

Vulnerability drivers & Intermediate impacts

Water abstractions for agriculture and other uses put pressure on water availability during periods of decreased precipitation, further reducing the surface and groundwater resources (Kristensen et al. 2018). In rivers, the fragmentation of the river habitat due to water flow regulation, flood mitigation measures and river channelisation compound with reduced surface water levels. These measures have historically been motivated by the necessity of flood protection, but also to enhance navigability (Limburg et al. 2013) and exploit surface waters to meet the increased societal demand for electricity by constructing hydropower plants (Kuriqi et al. 2020). The resulting severed connectivity restricts species migrations and nutrients flow, making the ecosystems' populations more vulnerable (Lake 2011; Flávio et al. 2017). Moreover, river fragmentation creates standing water bodies that more exposed to evaporation (Bond et al. 2008). A complex contributor to low flow is increased sedimentation, which reduces the depth available to the water body but is in turn influenced during drought by the reduced water flow, which allows for an increase of sediment deposition (Lake 2011). The level of sediments is connected to increased soil erosion at the watershed scale, with agricultural land-use and related farming practices an important cause of this (Flávio et al. 2017; Rashmi et al. 2022). In some cases, farmers' lack of awareness about agricultural impacts on freshwater ecosystems may contribute to the persisting use of intensive practices (Flávio et al. 2017). Agriculture also affects the quality of the environmental flow through its input of nutrients from fertilisers, which together with wastewater discharge are major sources of eutrophication (Hall and Murphy 2010; Sanseverino et al. 2016; Mosley 2015; Jeppesen et al. 2015; Flávio et al. 2017). Eutrophication, in turn, is a process that can cause harmful hypoxic events, capable of severely impacting animal and vegetation species (Lake 2011), although conditions can vastly differ based on the level of aeration available to the water body (Mosley 2015). This contributes to the decrease in water quality, affected also by the discharge of pollutants from agriculture, as well as from domestic and industrial water uses (International Commission for the Protection of the Rhine 2020; European Environment Agency, 2021). Given the important interdependency between freshwater ecosystems and the surrounding terrestrial ecosystems such as wetlands and riparian zones, vegetation water stress (Lake 2011; Čížková et al. 2013; Wang et al. 2014; Stella and Bendix 2019; Stirling et al. 2020; Wossenyeleh et al. 2021) in these ecosystems and (the consequent decrease in aquatic and riparian vegetation and functions) can ultimately affect environmental flow and therefore the health of freshwater ecosystems.

6.3 Data-driven model results

6.3.1 Identification of available impact data and exposure

The impact chains did not identify any apparent direct indicator for ecosystem health. As a proxy for this, we therefore used net primary production (NPP), since a reduction in ecosystem health would directly result in lowered primary production. Primary production is the entry point of energy and carbon into ecosystems. Net primary production is the amount of biomass or carbon produced by primary producers per unit area and time, obtained by subtracting plant respiratory costs (Rp) from gross primary productivity (GPP) or total photosynthesis. In this analysis, yearly NPPs from MODIS were masked with Corine Land Cover and spatially aggregated to NUTS-3 level for analysis. For terrestrial ecosystems Corine Land Cover “forest” classes were used to compute area fraction image (% of forest or wetlands in NPP 500m pixel resolution). For wetlands the “inland wetland” classes were considered. Only wetlands larger than 1 km^2 were considered.

6.3.2 Identification of risk drivers

For both ecosystems (forests and wetlands), the most important drivers for drought losses come from meteorological indices, particularly the ones related to precipitation and evapotranspiration (top block, Figure 56). These indices represent the water balance and thus directly the water available for vegetation and biomass growth (net primary production). Discharge related indices are not so important for wetlands, and this is in line with the nature of the wetlands considered, since these are mostly related to lakes rather than rivers.

Net primary production (NPP)

Plants are primary producers that, through photosynthesis, manufacture organic molecules such as carbohydrates and lipids from raw inorganic materials (CO_2, water, mineral nutrients). Primary productivity is thus a fundamental determinant of both the structure and functioning of terrestrial biomes. The energy and carbon of primary production supplies consumers, including humans, with the necessary fuel to support their metabolism while providing essential carbon compounds that form the bricks and mortar of living cells. In addition to solar radiation, the main abiotic factors that affect rates of photosynthesis and NPP are water, temperature, carbon dioxide concentration, and nutrients. Understanding the relationship between NPP and droughts is of paramount importance in investigating the future evolution of NPP (Cherlet M. et al 2018).

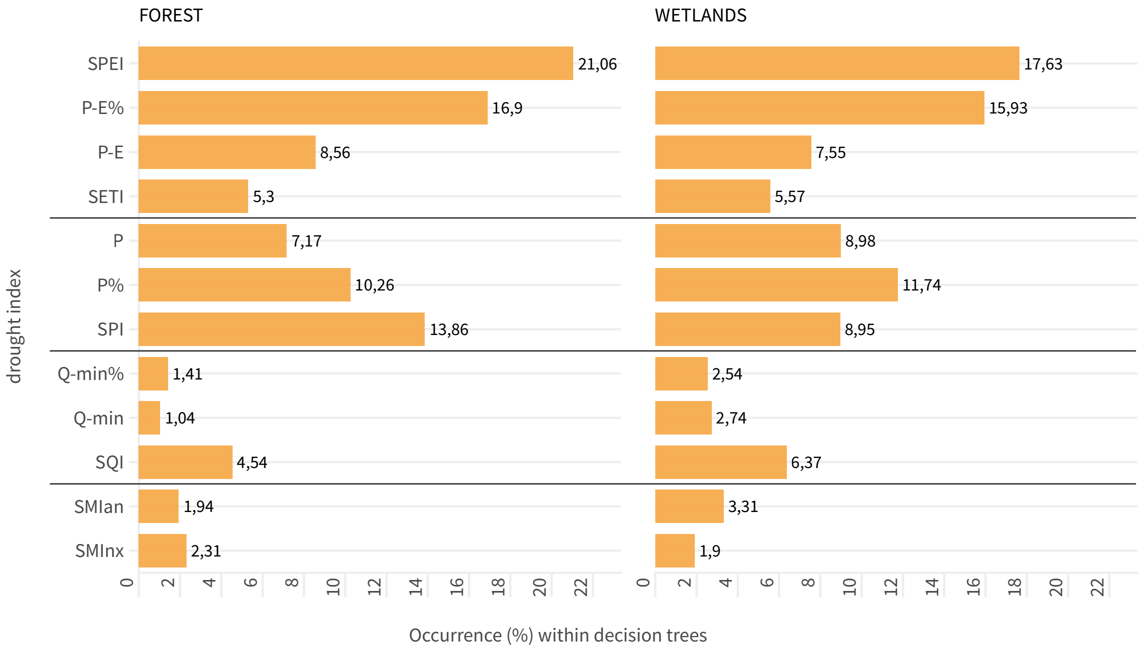


Figure 56:
Occurrence of drought indexes in the decision trees for terrestrial and freshwater ecosystems.
The group of indices related to Precipitation (P) and Evapotranspiration (E) is the most important for impact prediction on agriculture (see Annex I for details).

6.3.3 **Drought risk under current climate conditions**

Terrestrial Ecosystem

The highest relative average annual losses due to droughts (expressed as a percentage reduction of the average NPP) are expected in northern Sweden and south-eastern Europe, and to a lesser degree north and south of the Alps (Figure 58).

In the case of an extreme (1-in-50-year) event, these are also the places where considerable losses of up to 30% in NPP may occur (Figure 59). Southern Spain also stands out, with losses of up to 20% in NPP expected to occur on average once every 50 years.

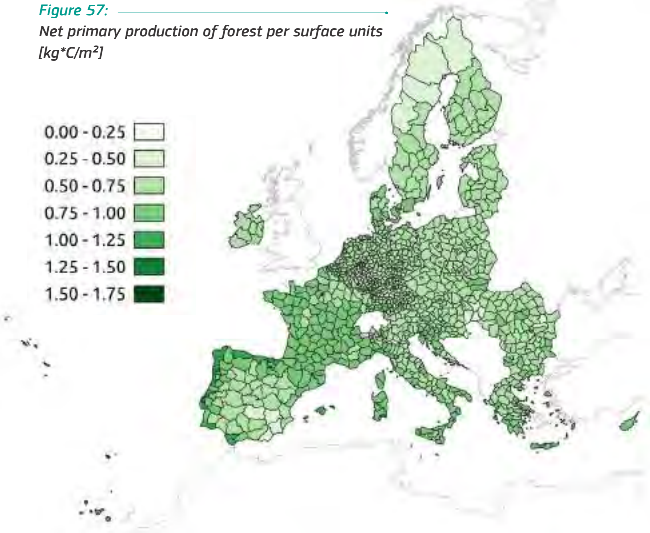


Figure 57:
*Net primary production of forest per surface units [kg*C/m²]*

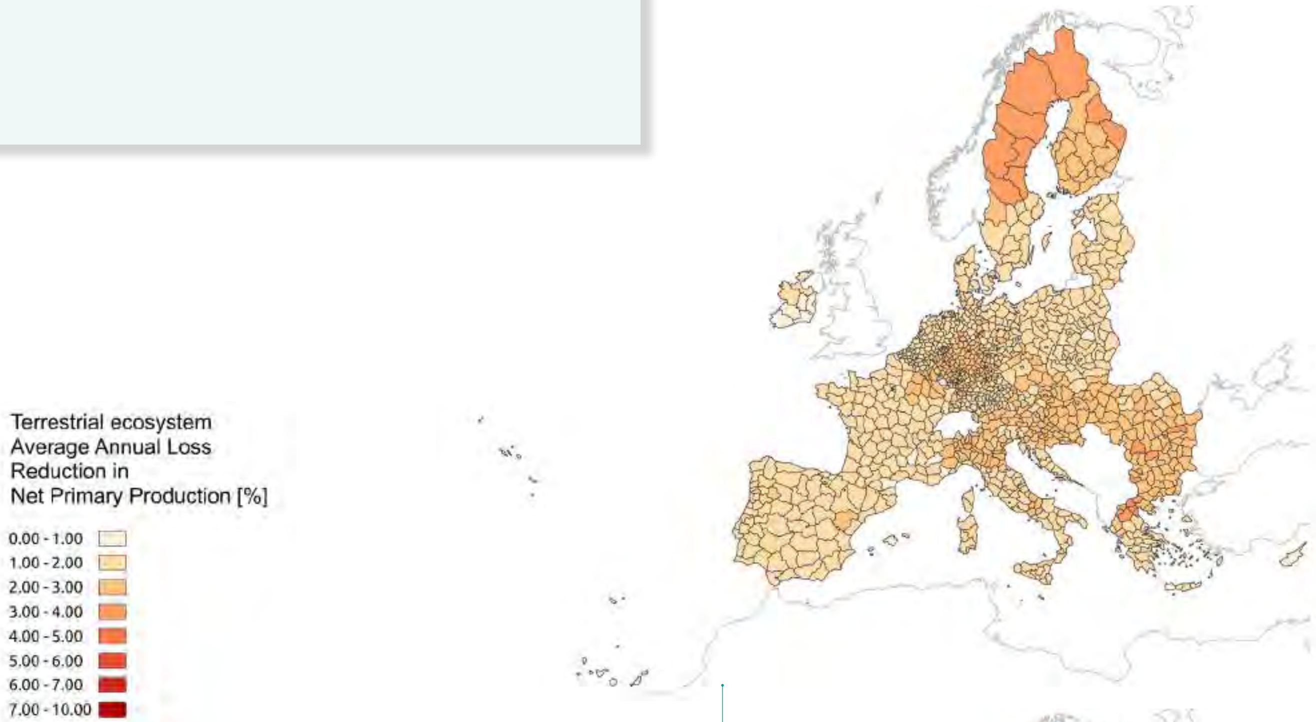
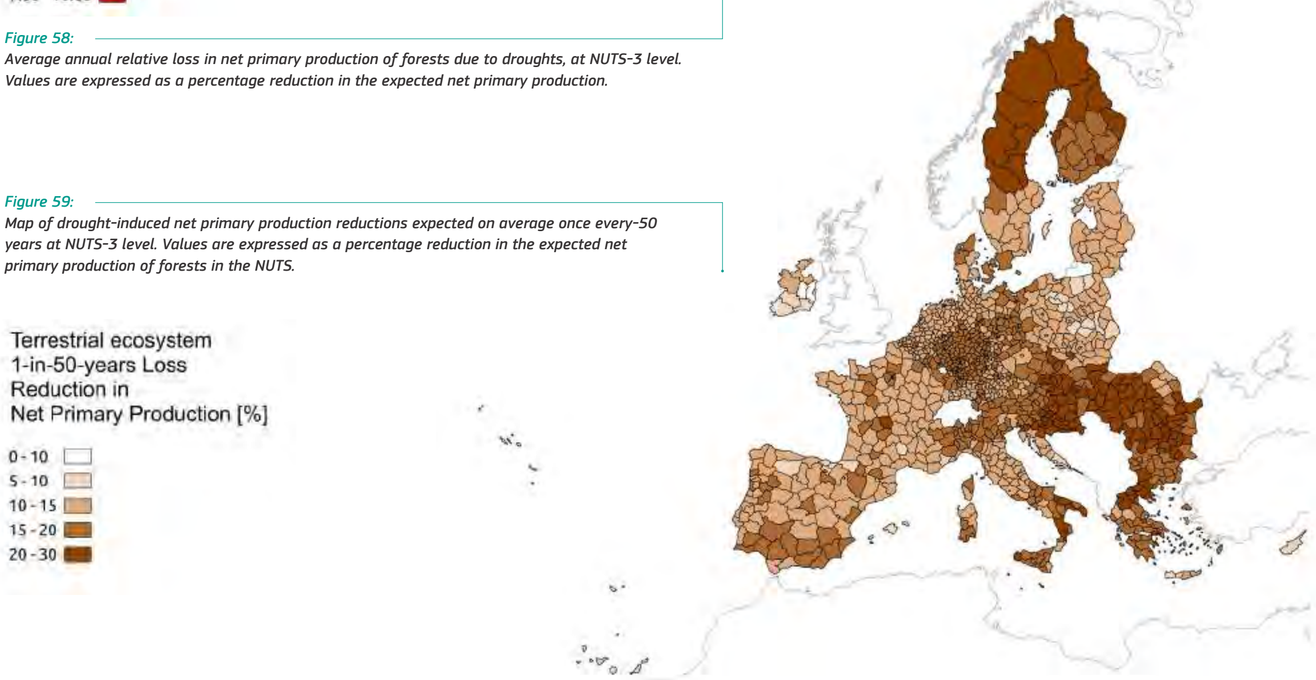


Figure 58:
Average annual relative loss in net primary production of forests due to droughts, at NUTS-3 level. Values are expressed as a percentage reduction in the expected net primary production.

Figure 59:
Map of drought-induced net primary production reductions expected on average once every-50 years at NUTS-3 level. Values are expressed as a percentage reduction in the expected net primary production of forests in the NUTS.



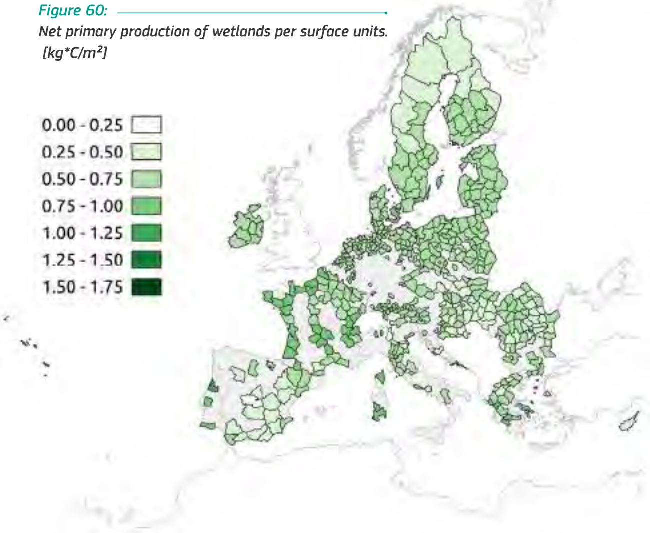
Freshwater Ecosystem

Similarly to forests, the highest average annual losses due to droughts (expressed as a percentage reduction in the average NPP over wetland areas) are estimated to be in northern Sweden, south-eastern Europe and southern Spain.

The same pattern is observed when analysing an extreme (1-in-50-year) impact event, with losses rising by up to 30% in Scandinavia.

Figure 60:

*Net primary production of wetlands per surface units. [kg*C/m²]*



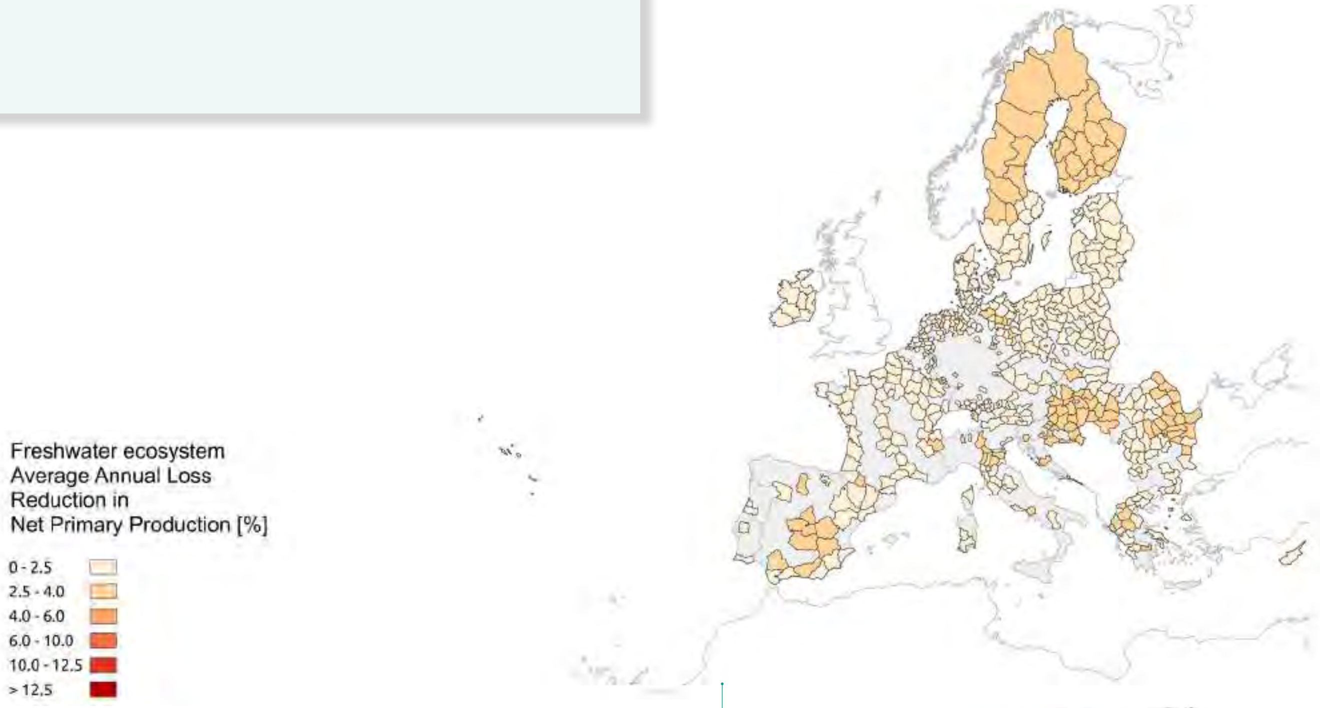
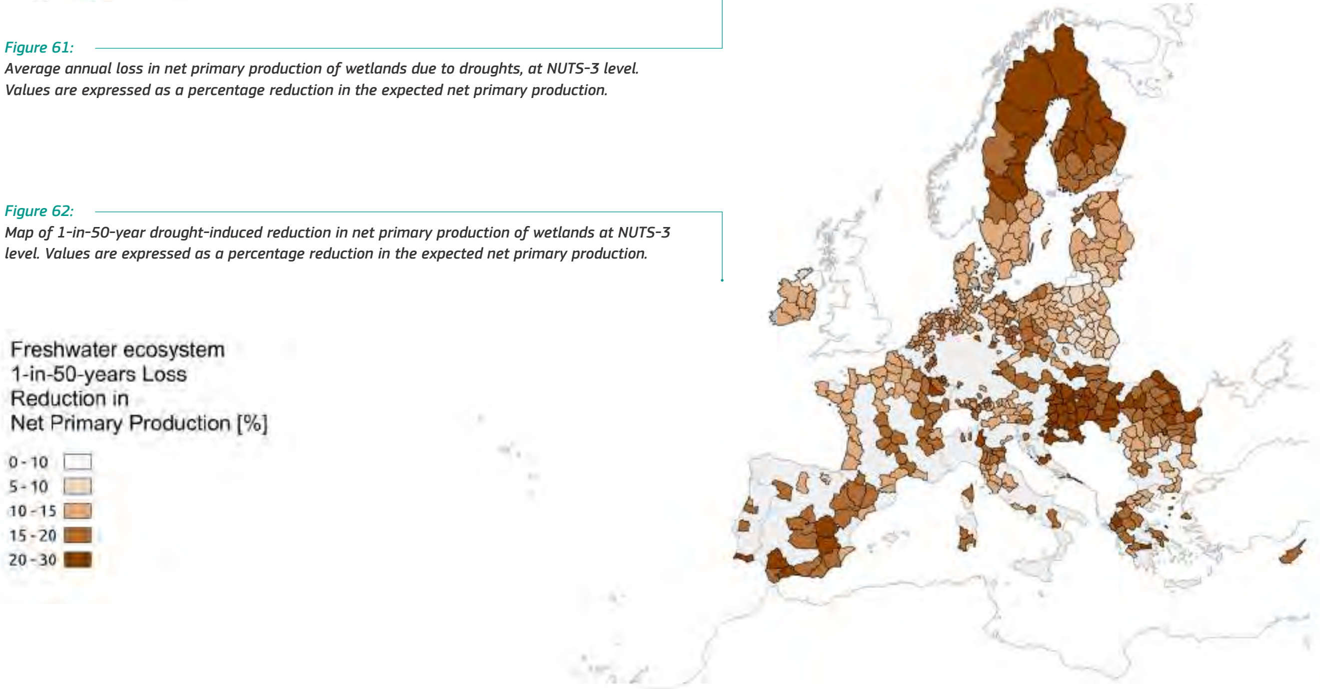


Figure 61:

Average annual loss in net primary production of wetlands due to droughts, at NUTS-3 level. Values are expressed as a percentage reduction in the expected net primary production.

Figure 62:

Map of 1-in-50-year drought-induced reduction in net primary production of wetlands at NUTS-3 level. Values are expressed as a percentage reduction in the expected net primary production.



6.3.4 **Drought risk under projected climate conditions**

Terrestrial Ecosystem

While moderate changes in losses of net primary production are observed mainly in central and eastern Europe, projections of risk under climate change reveal a considerable increase in drought-induced losses in southern Europe. Spatial distribution is largely influenced by the amount/type of forests exposed to drought. In relative terms, losses in the Mediterranean region will double or triple under 3 °C warming compared to the current risk (Figure 63).

No change, and even a decrease, is projected for northern Europe. This is broadly in line with the gradient seen in average SPEI6 values (see Annex II), though increased variability also likely plays an important role as well when it comes to ecological drought losses.

The PML curves (Figure 64) show variability depending on the climate models considered. The increase projected for southern Europe and the decrease for northern Europe counteract each other on EU scale, resulting in relatively similar PML curves for the three warming levels – with only slight increases in losses found for more frequent events under all scenarios.

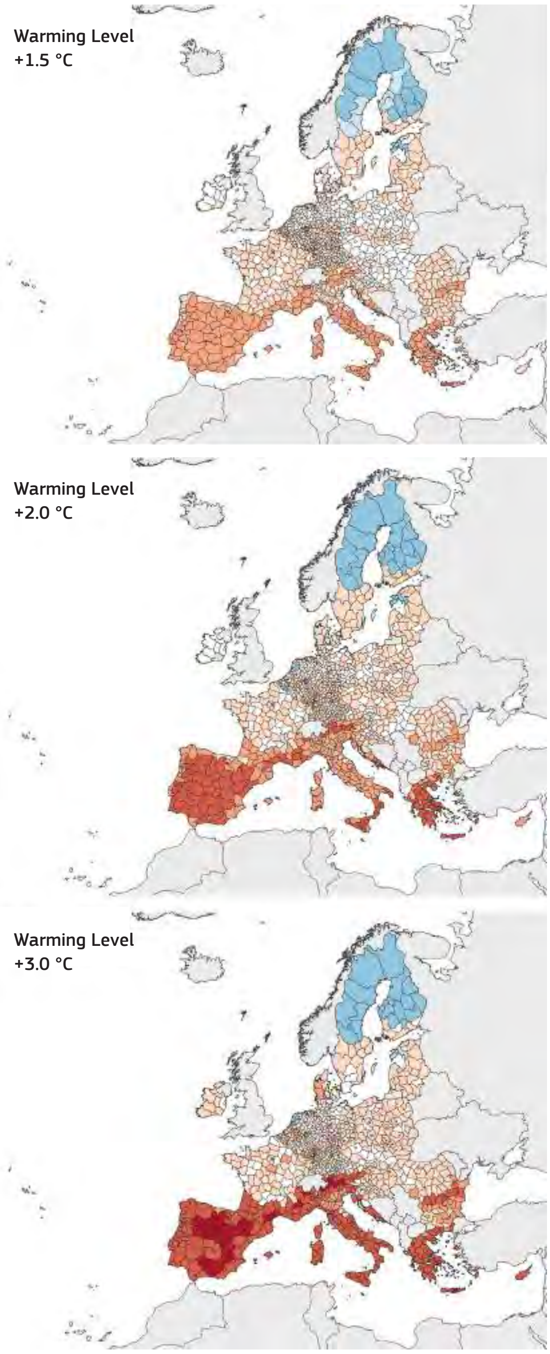


Figure 63:
Variation of drought risk for terrestrial ecosystems between current and projected conditions. Risk is measured as average annual reduction in net primary production of forest compared to the average expected value under current climate conditions. Results of future simulations forced with 11 climate models in RCP 4.5 and RCP 8.5 are averaged for each warming level (+1.5 °C, +2.0 °C, +3.0 °C). The analysis was conducted at NUTS-3 level, for those territorial units with sufficient data for computation.

Projected Loss / Current Loss

- 🟦 reduction of more than 25%
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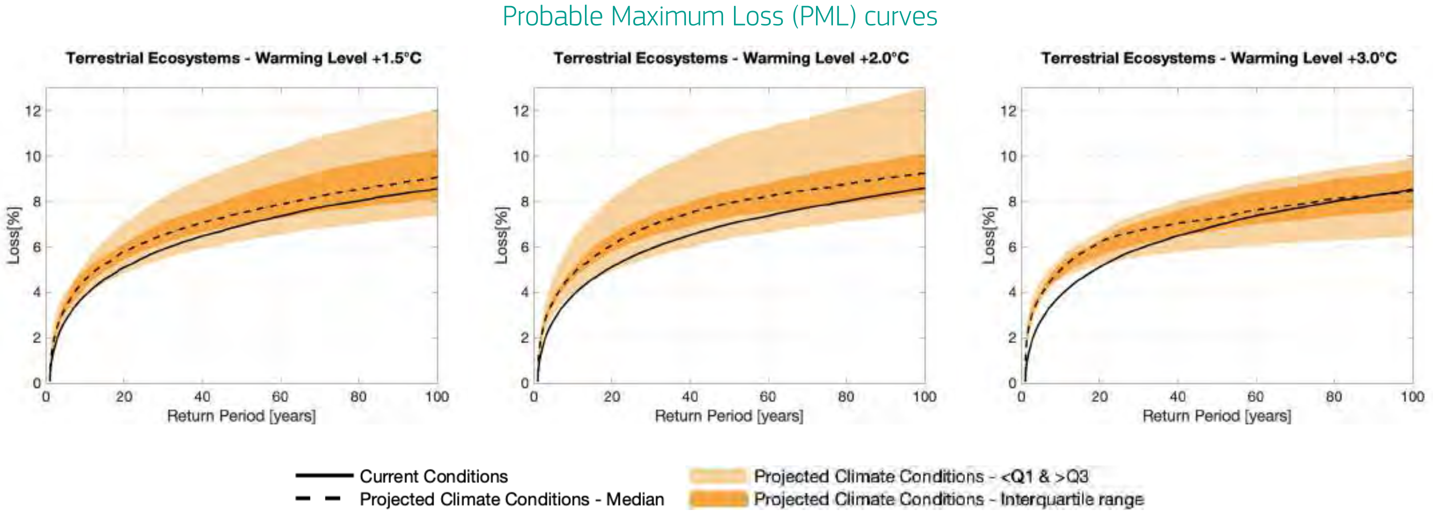

Figure 64:
EU-aggregated PML curves for forest net primary production under current and projected conditions for +1.5 °C, +2.0 °C, +3.0 °C warming level scenarios. The solid black line is the PML curve for the historical period, while the dotted black line traces out the median of future simulations forced with 11 climate models in both RCP 4.5 and RCP 8.5. The shades of yellow denote the climatic variability of future simulations: dark yellow is the interquartile, while pale yellow represents the lower and upper quarters.

Freshwater Ecosystem

Risk projections in terms of average annual losses of net primary production in wetlands are similar to those for forests, though the north-south divide is more pronounced (Figure 65). Risk is projected to rise with increasing warming levels in southern Europe, with the largest risk increase in the Mediterranean region. No change, and even a decrease, is projected for northern Europe. Particularly from at 2 °C or higher warming level a decrease in ecological drought risk is projected ranging from Ireland to Scandinavia and the Baltic states. This is again relatively similar to the SPEI6 pattern. (thus projected changes in precipitation within EU) relatively well. It seems that wetlands in the northern part of central Europe will be less affected by increased variability while the forest ecosystems there will suffer to a greater extent.

PML curves show high variability based on the climate models considered (Figure 66). The increase in southern Europe and the decrease in northern Europe counteract each other, the uncertainties remain large, but an overall change in direction for the higher losses for each return period is projected with increasing warming levels.

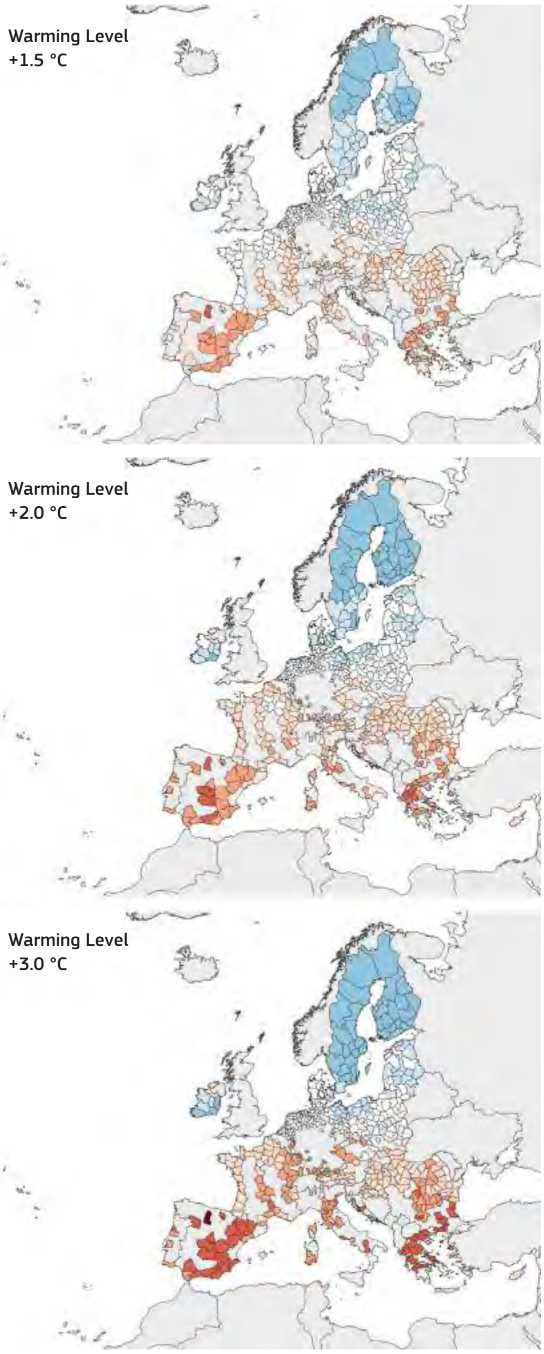

Figure 65:
Variation of drought risk for freshwater ecosystems between current and projected conditions. Risk is measured as average annual reduction in net primary production of forest compared to the average expected value under current climate conditions. Results of future simulations forced with 11 climate models in RCP 4.5 and RCP 8.5 are averaged for each warming level (+1.5 °C, +2.0 °C, +3.0 °C). The analysis was conducted at NUTS-3 level, for those territorial units with sufficient data for computation.

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- 🟥 increased by a factor of 2 to 3
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- ■ increased by a factor of more than 4

Probable Maximum Loss (PML) curves

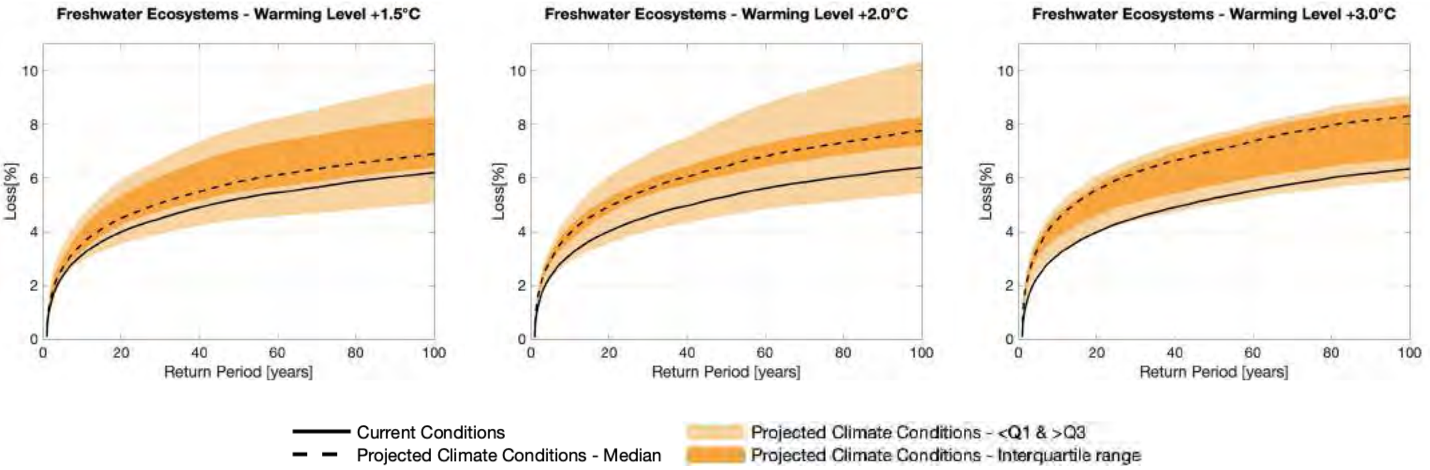

Figure 66:
EU-aggregated PML curves for wetland net primary production under current and projected conditions for +1.5 °C, +2.0 °C, +3.0 °C warming level scenarios. The solid black line is the PML curve for the historical period, while the dotted black line traces out the median of future simulations forced with 11 climate models in both RCP 4.5 and RCP 8.5. The shades of yellow denote the climatic variability of future simulations: dark yellow is the interquartile, while pale yellow represents the lower and upper quarters.

CHAPTER 7

Conclusions

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This atlas presents a comprehensive assessment of drought risks across the EU systems and regions. It uses impact chains and quantitative analyses to reveal the complex interplay of drought hazard, exposure, vulnerability, and their impacts on interconnected systems. The standardised methodologies developed in the atlas offer scalability, allowing their application at multiple levels, such as by countries or for single river basin. This flexibility enables the use of high-quality data and tailored strategies, advancing forecasting of impacts.

Across Europe, commonalities in drought impacts and drivers of risk emphasise opportunities for coordinated drought management and adaptation. The atlas identifies critical risk factors, enabling policymakers to target risk reduction effectively. The quantitative analysis shows that current drought risk levels are significant, with average annual losses posing economic and environmental threats. Human-induced climate change puts the Mediterranean region particularly at risk due to a clear drying trend seen with rising global warming levels, while northern regions face more diverse and varying effects (e.g. wetter but more variable weather conditions together with an expected increase in frequency and intensity of extremes). The more holistic analysis in the form of impact chains offers valuable entry points for drought risk management by identifying the underlying processes leading to risk and impacts.

As regards specific systems, **agriculture** faces substantial yield losses, with risks expected to increase in most of Europe in the future. Policies promoting precision agriculture and water resource diversification contribute to risk mitigation. For irrigated agriculture, drought-resilient practices and strategies such as volumetric pricing and efficient irrigation methods offer avenues for adaptation. Policies such as the EU Water Reuse Regulation could be promoted to increase diversification especially in coastal areas, where water would otherwise be discharged into the sea.

For **public water supply**, the connections between water abstractions and drought are complex, as drought can increase demand (and thus abstraction), while rationing restricts abstraction. The quantitative analysis reveals that the highest average annual increase in drought-induced water abstraction is currently observed in Spain, France and Romania. Under projected climate change conditions, water demand is estimated to significantly increase around the Mediterranean, where large increases in drought-induced water abstractions can be expected, especially with a global warming of +2 °C and +3 °C. Entry points for adaptation revolve around both quality and quantity of water, making the recast of the EU Drinking Water Directive an important tool. Moreover, various price effects will come into play as additional water treatment may be required and limited supply may increase prices.

In the **energy system**, both hydropower and nuclear power production are vulnerable to drought impacts. Projected changes in hydropower losses show very distinct differences between the south, and central/northern Europe. In the Mediterranean region hydropower losses are projected to increase with increasing warming level (up to three times current losses for a warming level +3 °C). However, in central and northern Europe, hydropower losses are projected to reduce. For nuclear power, greater variability in precipitation and higher potential evaporation driven by increased warming seem to increase risk in the whole of Europe. France is a hotspot, with nuclear power losses projected to increase between two and three times with respect to current conditions. Adaptation measures, including dry or hybrid cooling systems, could reduce vulnerability.

For **river transportation** in the Rhine-Meuse area significant disruptions are already experienced under current conditions, although the relative average annual losses in transported goods generally stands at below 2.5%. Under projected climate scenarios, risk to river transportation may decrease in relative terms, but Germany, Belgium and France will remain the most affected countries. Conditions are projected to progressively worsen for the Danube, especially in the upper part of the basin due to decrease in snow melt contribution. The most promising potential for adaptation consists of varying fleet composition (vessels adapted to low flow) and supply stock management.

The health of **forest** and **wetland ecosystems**, measured through drought-induced reduction in net primary production, reaches up to 4% under current climate conditions. Around the Mediterranean, a tripling of the drought risk is projected in 3 °C warmer world. Buffer zones and diversified water resources show potential for adaptation.

Looking at drought risk in the various regions of the EU with a multi-sectoral perspective, **southern Europe** (Mediterranean area) presents the highest drought risks in the systems considered. Moreover, this region is set to have the largest increases in drought risk due to climate change driven by a general drying of the region. Within this area, the Iberian Peninsula (and Spain in particular) has the highest level of drought risk under both current and projected climate conditions. In **northern Europe** (Scandinavia and the Baltic area), projections show limited changes in drought risk between current and future conditions (compared to that for southern Europe), with less clear signals. **Eastern and western Europe** are expected to experience more complex effects, with some projections showing increased drought risks, while others show similar or even decreasing risk, owing to the interplay of drying/wetting dynamics and greater in precipitation. Notably, Romania already has relatively high risks for several sectors, and future projections show an increase in risk (e.g. for agriculture, water supply, hydropower, terrestrial and freshwater ecosystems). France is a transition country, where the higher risk estimated in the south is found also in the north at higher warming levels (for agriculture, water supply, terrestrial and freshwater ecosystems). France is also a hotspot for nuclear power production, with losses projected to significantly increase in future climate conditions.

It is important to be aware of the **limitations** of the assessments presented here, particularly related to the future projections. Firstly, the future projections are based on climate model outputs (EURO-CORDEX) and the hydrological model outputs derived from those. These projections are driven by increases in human greenhouse gas emissions and consequential temperature increases. As such, any other future developments that might influence exposure and the systems' vulnerabilities (technological development, CO_2 fertilisation, changes in exposure, management) have not been taken into consideration in this atlas. In addition, uncertainties in the future climate projections affect the outcomes. For instance, snowpacks at high altitude or latitude may at first contribute to more water resources but may collapse when complete melting nears. Where and when this happens is crucial for various systems downstream but is nevertheless subject to considerable uncertainties. Likewise, changes in the climate may result in unprecedented combination of driver and extreme events occurring in the future and, since these have never before been witnessed, no impact can be estimated for them. To facilitate adequate risk assessments for basing drought management policies on, systematic monitoring and collection of data on droughts and their impacts (at a pan-European scale) is crucial since a lack of available continuous quantitative data is one of the most limiting factors in assessments of this nature.

As shown in this atlas, droughts can have diverse and wide-ranging impacts. As such, we recommend taking a systemic, cross-sectoral approach when it comes to assessing and managing drought risks, focusing on addressing both water availability and needs (including policies to reduce competition across sectors). Whilst this atlas evaluated risk per system, we recommend further exploring the links and cascading risks between systems, as the impact chains illustrate that there are many overlapping root causes and drivers of risk. A holistic approach of this sort to drought risk management, which considers possible interactions with other relevant shocks and is ideally complementary to flood risk management is required to avoid unintended trade-offs in risks for systems and maladaptation in general.

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Glossary

Adaptation

In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects (IPCC 2022 AR6 WGI-II-III).

Adaptation options

The array of strategies and measures that are available and appropriate for addressing adaptation. They include a wide range of actions that can be categorised as structural, institutional, ecological or behavioural (IPCC 2022 AR6 WGI-II-III).

Average annual loss (AAL)

Average annual loss (AAL) is the average of a long time series that includes losses of all possible years (or events), even the rarest ones. AAL corresponds to the area (integral) underneath the curve Exceedance Probability (EP) curve.

Climate model

A qualitative or quantitative representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrisations are involved. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate and for operational purposes, including monthly, seasonal and interannual climate predictions.

Climate projections

Simulated response of the climate system to a scenario of future emissions or concentrations of greenhouse gases (GHGs) and aerosols and changes in land use, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realised.

Drought

An exceptional period of water shortage for existing ecosystems and the human population (due to low rainfall, high temperature and/or wind).

- Meteorological drought
  A period with an abnormal precipitation deficit.
- Agricultural and ecological drought
  Depending on the affected biome: a period with abnormal soil moisture deficit, which results from combined shortage of precipitation and excess evapotranspiration, and during the growing season impinges on crop production or ecosystem function in general.
- Hydrological drought
  A period with large runoff and water deficits in rivers, lakes and reservoirs.
- Megadrought
  A very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more (IPCC 2022 AR6 WGI-II-III).

Exceedance Probability (EP)

Exceedance Probability (EP) is the probability that a loss can be exceed in a year (or event). It is displayed as a curve, to illustrate the probability of exceeding a range of losses, with the losses running along the X-axis, and the exceedance probability running along the Y-axis.

Exposure

The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected (IPCC 2022 AR6 WGI-II-III).

Hazard

The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources (IPCC 2022 AR6 WGI-II).

Impacts

The consequences of realised risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather/climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes, and can be adverse or beneficial (IPCC 2022 AR6 WGII-III).

Probable Maximum Loss (PML)

Probable Maximum Loss (PML) curve is a standard risk metric used in catastrophe modelling and insurance business activities. It refers to a loss that could be exceeded during an event with a specific return period (e.g. a 1-in-10 years loss). It presents the same information contained in the Exceedance Probability (EP) curve (which provide the probability that a loss can be exceeded in an event or in a year), but in the case of the PML curve rarity is expressed in return period (RP) instead of probability (p=1/RP) and this allows a better focus on the tail of the curve, i.e. rarest events with highest RPs and very low probability. For example, a 100-year occurrence PML of $3 million means that there is a 1-in-100 (1 percent) chance of a loss of at least $3M.

Resilience

The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management (IPCC 2022 AR6 WGI-II-III).

Risk

The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species (IPCC 2022 AR6 WGI-II-III).

Vulnerability

The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC 2022 AR6 WGI-II-III).

Acronyms & Abbreviations

AAL	Average Annual Loss
AI	Aridity Index
AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
AWC	Available Water Capacity
CASA	Carnegie-Ames-Stanford Approach
CORDEX	Coordinated Regional Climate Downscaling Experiment
CORINE	Coordination of information on the environment
CEMS	Copernicus Emergency Management Service
E	Evapotranspiration
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EDII	European Drought Impact Report Inventory
EDO	European Drought Observatory
EDORA	European Drought Observatory for Resilience and Adaptation
EEA	European Environment Agency
ENV_WATABS_RB	Water abstraction by river basin district
EP	Exceedance Probability
EQI	European Quality of Government Index
ERA5	Fifth ECMWF Re-Analysis
ESDAC	European Soil Data Centre
EU	European Union
EU27	27 member countries of the European Union
EUROSTAT	Statistical office of the European Union
FAO	Food and Agriculture Organization of the United Nations
FP	False Positive
GAEZ	Global Agro-Ecological Zoning
GDO	Global Drought Observatory
GDP	Gross Domestic Product
GHG	GreenHouse Gas
GPP	Gross Primary Productivity
GWL	Global Warming Level
H	High

IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation Of Nature
IWT	Inland Water Transport
L	Low
LOWESS	Locally Weighted Scatterplot Smoothing
ML	Machine Learning
MODIS	Moderate resolution Imaging Spectroradiometer
NUTS	Nomenclature of Territorial Units for Statistics
NPP	Net Primary Production
P	Precipitation
PET	Potential Evapotranspiration
PML	Probable Maximum Loss
PPS	Purchasing Power Standard
PRIS	Power Reactor Information System
Q	Discharge
RBD	River Basin District
RCM	Regional Climate Model
Rp	Respiratory costs
RCP	Representative Concentration Pathway
SEI	Socio Economic Impact
SETI	Standardized Precipitation Evaporation Ratio Index
SM	Soil Moisture
SMI	Soil Moisture Index
SPEI	Standardized Precipitation Evaporation Index
SPI	Standardized Precipitation Index
SQI	Standardized Streamflow Index
SSMI	Standardized Soil Moisture Index
T	Temperature
TP	True Positive
UNDRR	United Nations Office for Disaster Risk Reduction
UNECE	United Nations Economic Commission for Europe
WGI - WGII - WGIII	Working Group I - Working Group II - Working Group III
WL	Warming Level
WHO	World Health Organization
WMO	World Meteorological Organization

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Annex I
Methodological notes

Conceptual models of impact chains

The conceptual models of drought risks constructed as part of the EDORA methodology aim to identify and describe the risk associated with drought events for each sector and system, since every system may suffer from highly different impacts from the same type of hazard. The conceptual models build on the impact chain approach, adapted from Hagenlocher et al. (2018). Impact chains are analytical tools in which drivers of risk are identified and categorized into the components of risk, following the conceptualization of risk derived from the UNDRR Global Assessment Report and IPCC AR6 framework, where disaster risk is understood as resulting from the interaction of hazard, exposure, and vulnerability (UNDRR Global Assessment Report, 2015; IPCC, 2023). The identification of drivers and their interlinkages is performed through extensive literature review and stakeholder or expert consultation. The causal relations and feedback loops between drivers are then represented in a visual model to facilitate risk assessment. To capture the complex processes that result from the interactions between the different driver categories that contribute to risk, the impact chain methodology introduces the additional category of intermediate impacts, visualised as a separate box. From a conceptual standpoint, the methodology stresses the importance of defining risk for the system under investigation (i.e. who or what is at risk; of what; and due to what?).

The first step in developing the conceptual models built on the results of the systematic literature review carried out during the first phase of the EDORA project; these were then reviewed to identify the most pressing drought impacts for each system and sector, thus informing the definition of risk for each case. The literature database for each system/ sector was then greatly expanded through searches on selected topics of relevance, identified with, among other things, inputs from key experts in each sector/ system, who were consulted bilaterally and shared their opinions on the most pressing risks related with drought events in their sector/system of reference, helping to identify the most important drivers of risk. The resulting number of documents consulted for the construction of each impact chain ranged from 30 to over 100, and included peer-reviewed articles, reports, book chapters and other forms of grey literature. The information collected through the expert consultations and the information emerging from the literature analysis were cross-validated and integrated using an iterative process. The identified risks and drivers of risks were utilised to create the first version of the visual model.

The next step was the validation of the conceptual models. This was done through a series of online workshops organised in September 2022. For each system and sector, a group of experts was selected and invited to participate in a two-hour meeting. These experts included but, were not restricted, to those who contributed during the initial bilateral meetings. The selection of experts was based on relevancy and recency of contributions in their respective fields, as emerging from the desk research and the Network of Drought Observatories in the EU event of June 2022. Altogether, five different European countries were represented in the workshops, as well as some EU-level bodies (the European Central Bank and the Joint Research Centre). Table 1 offers a breakdown of participation for each event. To allow preparation for the relative workshop, the first version of the impact chain models and a supporting presentation were shared with the participants approximately a week before each event. During the series of workshops, the conceptual models were then progressively presented by members of the EDORA consortium and discussed in a plenary session. This allowed clarification of any remaining doubts about the drivers’ interlinkages and validation of the models, which were reviewed to incorporate the results and suggestions from the workshops.

Title of the event	Date	Number of participants (excluding EDORA consortium members)	Participants' affiliations
Drivers of risk and impact chains workshop - Drought risks for forest ecosystems	07.09.2022	6	-University of Wuerzburg-Max Planck Institute for Biogeochemistry -Wagenigen University -Swiss Federal Institute for Forest, Snow and Landscape Research WSL
Drivers of risk and impact chains workshop - Drought risks for freshwater ecosystems	12.09.2022	3	-Institute of Environmental Assessment and Water Research -Joint Research Centre -Swedish University of Agricultural Sciences
Drivers of risk and impact chains workshop - Drought risks for inland water transport	13.09.2022	3	-Bundesanstalt für Gewässerkunde (BfG) -Joint Research Centre
Drivers of risk and impact chains workshop - Drought risks for rainfed agriculture	15.09.2022	3	-Romanian Agrometeorological Department (Meteo Romania) -German Meteorological Service (DWD) -Wageningen University
Drivers of risk and impact chains - Drought risks for irrigated agriculture	16.09.2022	4	-Georg-August-University Göttingen -European Central Bank -Joint Research Centre
Drivers of risk and impact chains workshop - Drought risks for public water supply	07.09.2022	3	-Wasserversorgung Rheinhessen-Pfalz GmbH -Viacqua SpA -KWR Water Research Institute
Drivers of risk and impact chains workshop - Drought risks for the energy sector	08.09.2022	4	-Vienna University of Technology -Polytechnic University of Milan -Joint Research Centre

Table 1 - Annex I: Date and number of participants in each workshop held for impact chain validation.

Data driven approach to risk evaluation

The data-driven approach used machine learning (ML) models, specifically decision trees, to establish a quantitative relationship between observed impacts (expressed as a Boolean variable) and observed hazards (represented by continuous drought indices). This process entails the acquisition of insights into the vulnerability of the impacted systems and sectors to drought-related hazards. Subsequently, this acquired relationship is applied to estimate the associated risk under specific climatic conditions, encompassing both present and future scenarios.

Ideally, this analytical procedure should be conducted at the highest attainable spatial and temporal resolution, such as the detailed NUTS level or even a gridded format. However, its implementation is constrained by the lowest resolution inherent in either the impact or hazard data (mostly by impact data). Furthermore, given that the temporal extent of time series data is frequently constrained, particularly in the case of observed impact data, it is advisable to consolidate data by grouping regions with similar vulnerability characteristics. This grouping allows for the expansion of the sample size, enabling the data-driven model to be trained more robustly and effectively.

The first step entails the computation of drought hazard indices.

Multiple physical drivers for drought were evaluated: precipitation, potential evaporation, streamflow, and soil moisture. These drought hazard drivers were also identified in the impact chains of the various systems. For each of these physical drivers, a multitude of indices was determined. The indices were based on ERA5 data (30km spatial resolution) and the EDO/GDO repository (output of the LISFLOOD model, at a 10-day time step). Hydro-meteorological data were acquired for:

- Precipitation (P, ERA5)
- Potential Evapotranspiration (PET, ERA5)
- Soil moisture (SMIx, EDO, CEMS)
- Streamflow (Q, EDO, CEMS)
- Temperature (T, ERA5)

Note that temperature (T) was excluded from the final results due to its nature as a proxy for heat and its limited relevance as a hydrometeorological index due to its strong relationship with PET.

With this hydro-meteorological data, a large variety of indices (absolute, relative, standardised) were calculated in order to be used as potential drivers in the decision trees. Data were first aggregated to monthly data. For ERA5, this was done by downloading the monthly totals and averaging to NUTS-3 regions. The EDO/GDO data were in 10-day time steps, and were aggregated for streamflow (lowest discharge among three 10-day data points for the pixel with the highest average discharge in the NUTS-3 regions) and for soil moisture (average over data points and in the NUTS-3 regions).

With this monthly data at NUTS-3 level, accumulation periods of 1, 3, 6 and 12 months were applied, resulting in the first (absolute) indices for precipitation, evapotranspiration, and precipitation minus evapotranspiration. Next, relative indices were determined by calculating the difference with the median (with median set at 100%). Specifically, NPI (normalized precipitation index), NPEI (P-PET % deviation), NETI (% P/PET) and NEI (% PET), NQI (% Q) and NSMI (% of median SMI) were computed. Lastly, standardised indices were determined for all accumulation periods. Specifically, SPI (standardised precipitation index), SPEI (P-PET), SETI (P/PET) and SEI (PET), SQI (Q) and SMIan (SMI anomaly) were determined.

Annual data were then created to match the temporal resolution of the observed impacts. This involved aggregation of the monthly indices to generate annual values through various methods, including:

- Individual monthly indices (resulting in 12 values per indicator)
- Mean of monthly values
- Minimum of monthly values (maximum for PET)
- Duration expressed as the number of months below (or above for PET) zero (for standardised indices) or 100 (for relative indices)
- Deficit computation, involving the summation of index values below (or above for PET) zero or 100.

The second step involved the identification of impact data and consequently exposure. Availability of open and free data related to the main variable impacted by drought (as identified by the impact chains) was first screened. Depending on the sector, either a key variable (e.g. crop yield for the agricultural sector) or a proxy (e.g. net primary production derived from satellite data for the ecosystems) was retrieved. Consistent, continuous data on drought-related impacts are key to calibrating the approaches used to quantify drought risk, especially at the pan-European scale. Therefore, only impact information with lengthy continuous data (over at least a decade, preferably several decades) at high spatial (preferably NUTS-3 or subnational) and temporal (preferably monthly, otherwise yearly) resolution was considered. For an overview of the impact data used per system, see Annex II.

It is imperative to underscore that the availability of consistent, continuous data regarding drought-induced impacts is paramount in calibrating the methodologies employed for quantifying drought risk, particularly when addressing the Pan-European scale. For a comprehensive overview of the impact data utilized in each system, see Annex II.

Exposure is directly linked to the identified impact dataset. For systems where impact data were derived from continuous Eurostat data, the average value of the appropriate variable (e.g. production for agriculture; water abstraction for water supply) for the last five years was used to define the exposure. For other systems, specific exposure maps (e.g. related to location of hydropower dams, thermal power plants, specific ecosystems) as identified in the impact chains, were considered.

The third step was to define vulnerability clusters.

Selection of relevant vulnerability factors to be used in the clustering was derived from the impact chains, where the most important vulnerability factors for the drought risk were identified. Then, based on data availability (only free and public data were considered), spatial datasets of these vulnerability factors (or proxies for such factors) were selected.

These vulnerability clusters are characterized by similar vulnerability profiles (presumably, the regions within one cluster have comparable drought hazard-impact relationships) and are not necessarily contiguous in terms of geographical distribution. Subsequently, spatial datasets corresponding to these vulnerability factors, or suitable proxies for these factors, were selected based on data availability, with a strict emphasis on utilizing free and publicly accessible data sources.

To create the clusters, each vulnerability dataset was split into two ranges (values smaller and values larger than median). This resulted in the creation of n^2 potential clusters (with n being the number of vulnerability factors used). In practice, not all the possible combinations can be found, and the actual number of clusters is typically lower. In systems where multiple clustering options were possible (e.g. based on economy, physical threats, or both), an analysis was performed for each of the potential options.

The ML approach was then applied to all the potential cluster maps. The final vulnerability cluster map (treated here as a hyperparameter of the model) is the one that provided the best overall result (in terms of precision or balanced accuracy).

$$Precision = \frac{TP}{TP + FP}$$

$$Balanced\ Accuracy = \frac{\left(\frac{TP}{TP + FN}\right) + \left(\frac{TP}{TP + FP}\right)}{2}$$

Where:
TP= True Positive and FP = False Positive,
TN = True Negative and FN = False Negative

The fourth step involved calibration of the ML models by sector and by vulnerability cluster. The methodology can be summarised through the following points:

1) The continuous impact time series was first detrended in order to correct for shifts over time (e.g. related to technological advancements). This was generally carried out using a locally weighted scatterplot smoothing algorithm (LOWESS). This basically yielded an expected value for each year, from which the deviation (in %) could be derived. For some systems, another type of expected value was determined. For instance, for nuclear power the total produced power plus the total of all losses was determined.

2) To assess drought risk under future climate conditions, we explored an ensemble of regional climate models (RCMs). In total, 11 models from EURO-CORDEX (Jacob et al. 2014) were used, with two representative concentration pathways (RCPs), these being RCP 4.5 and RCP 8.5, for each model. Next, the impact data were reclassified into percentage loss (as compared to the expected value from LOWESS) exceedance categories. For example, in agriculture we considered the following categories: no yield loss, and loss > x %, where x = 0, 2.5, 5, 7.5, 10 … 65.
The percentage losses were adapted by sector, considering the observed range of losses.

3) The impact categories were then converted to a binary classification (i.e. loss either exceeding a threshold or not). This resulted in an impact record per severity category (i.e. yield loss exceeding 10%, 20%, etc.). The data were subsequently pooled into vulnerability clusters.

4) The decision tree algorithm (Decision Tree Classifier from sklearn Python package) was subsequently used per cluster and impact category to identify the hazard conditions (a specific set of drought indices and relevant thresholds) likely to create impacts of a selected severity. Risk identification was thus turned into a classification problem. The decision trees were optimised on precision or balanced accuracy (as set out in the equations above) with the aim of minimising false positives (detecting impact when there was no impact). Occasional misses (i.e. undetected impacts) were less penalized, recognizing the influence of non-drought factors contributing to observed reductions in the productivity of systems/sectors at risk (e.g. a reduction of crop yield may be caused by flooding or a reduction in hydropower may be due to a market shock). This approach ensures a realistic and conservative estimation of the drought-impact relationship. Decision trees are non-compensatory machine learning algorithms that prioritize the identification of the most influential predictors and therefore employ predictor thresholds to predict drought impact.

5) To determine the best hyperparameters of each decision tree, a grid-search was conducted to find the best combination of selection criterion ('gini', 'entropy', 'log_loss'), splitter ('best', 'random'), and depth (2, 3). The minimum sample split was set at 2, the maximum features at 1, and a balanced class weight was used. The trees were optimised based on both precision and balanced accuracy, with the best result picked after manual screening.

6) While decision trees have the capacity to capture non-linear relationships and interconnections among the factors contributing to impact, it is important to acknowledge their limitation in identifying a single specific set of hydrometeorological conditions that leads to impact, despite the existence of multiple combinations of conditions that can result in the same impact. To address this limitation, we employed an ensemble approach. Specifically, we constructed a forest of 30 decision trees, each trained on bootstrapped subsets of the data.

7) These decision trees, trained at the cluster level, were subsequently utilized to assess the risk across all NUTS regions within the cluster, including those lacking training data. They were applied to the entire length of the hazard time series of that NUTS (1979 to 2021), rather than just the training dataset for which the (usually more limited) impact data overlapped with the hazard data. In addition, they were applied on all NUTS regions that fell within a cluster (also the ones for which no training data were present). Also, they were applied to projected hazard time series corresponding to various Representative Concentration Pathways (RCPs) and warming levels (WLs), denoted as RCP 4.5 WL 1.5, RCP 4.5 WL 2.0, RCP 8.5 WL 1.5, RCP 8.5 WL 2.0, and RCP 8.5 WL 3.0.

8) For each climate scenario, NUTS region, and impact category, this process yielded a set of 30 series (one for each decision tree) of impact estimates (designated as 1) and no-impact estimates (designated as 0) for each analysed year. Subsequently, a weighted average over these 30 series was computed to derive a probabilistic assessment of the likelihood of impact for each year, impact category, NUTS region, and climate scenario. To ensure a conservative approach to risk analysis, the weighting was based on the precision of each of the 30 decision trees. Consequently, this step generated, for each scenario and NUTS region, an annual likelihood assessment of exceeding the evaluated impact category.

9) With the annual probability estimates in hand, risk assessments were conducted, yielding measures such as the Average Annual Loss (AAL) and the Probable Maximum Loss (PML) curves. The annual loss is calculated for each year by integrating the probabilities of each impact category across the different impact severity categories (e.g. 5% loss, 10% loss, etc.). The AAL is then determined by averaging these annual losses.
Average Annual Loss (AAL) is basically the average of a (decades-long) time series of annual drought losses (often zero, sometimes very high, sometimes in between). Note that this implicitly assumes that conditions are relatively stable over the considered time period. Because of this, it is calculated for periods of 30 years for the reference situation (1981-2010) or around (15 years before, 15 years after) a specific year when a certain warming level is achieved. AAL thus aggregates the severity of drought losses with their probability (occurrence). In this atlas, this is done for each NUTS region separately, resulting in maps with AAL per NUTS region.

10) To compute the PML, a frequency analysis was performed on the time series data to ascertain the loss associated with a specified return period. The analysis revealed that a lognormal distribution offers the best fit, based on the Kolmogorov-Smirnov test.
Probable Maximum Loss (PML) curve refers to a loss that can be exceeded during an event with a specific return period (e.g. a 1-in-10 years loss). It is very similar to Exceedance Probability (EP) curve (which provide the probability that a loss can be exceeded in an event or in a year), but rarity is expressed in return period (RP) instead of probability (p=1/RP) and this allow to focus on tail of the curve, i.e. rarest events with highest RPs. For example, a 100-year occurrence PML of $3 million means that there is a 1-in-100 (1 percent) chance of a loss of at least $3M.

11) The aforementioned computations yield AAL and PML values for each (NUTS) region. Additionally, a comprehensive pan-European AAL and PML were determined by aggregating yearly losses and applying the previous steps to the entire Europe.

12) To identify the most influential hazard drivers of drought impacts, an analysis was conducted to assess the frequency with which each hazard index was selected within the decision trees.

Synergies and complementarities between conceptual and data driven models.
While the qualitative impact chain approach aims to describe the complete risk system in a holistic way, the quantitative data-driven approach aims to estimate the severity of the risk in relation to a specific impact for which data are available. These complementary methods provide a solid understanding of both causes ("what" is drought risk?) and distribution ("where" is drought risk?) of drought risks in Europe. Moreover, the impact chain models enable contextualisation of the quantitative risk estimations, thus returning an overview of the "missing pieces" of the risk puzzle. In fact, the impact chain approach visualises the drivers that contribute to risks in each system. Thanks to these visualisations, it was possible to identify which elements should be included in the data-driven approach, and which should be excluded due to data availability challenges.

Complementarily, the machine learning approach enables estimation of (the heterogeneity of) the size of the drought risk within Europe, supporting a region-specific addition to the impact chains. While identifying hotspots and quantifying risk severity can be an important decision support tool for drought risk policies (they give an idea of the size and location of the problem), the impact chains offer entry points for the identification of effective drought risk management efforts, hinting at possible multiple benefits and cross-sectoral win-win solutions. In this sense, the models can serve a double function, informing the assessment on one hand, and acting as a conceptual and communication framework for the identification of risk reduction and adaptation options with policymakers on the other.

Current and projected risks
To assess drought risk under future climate conditions, we explored an ensemble of regional climate models (RCMs). In total, 11 models from EURO-CORDEX (Jacob et al. 2014) were used, with two representative concentration pathways (RCPs), these being RCP 4.5 and RCP 8.5, for each model.

RCM	Driving GCM	1.5 °C RCP4.5	1.5 °C RCP8.5	2 °C RCP4.5	2 °C RCP8.5	3 °C RCP4.5	3 °C RCP8.5
CCLM4.8-17	CNRM-CERFACS- CNRM-CM5	2035	2029	2057	2044	NA	2067
	ICHEC-EC-EARTH	2033	2026	2056	2041	NA	2066
	MPI-M-MPI-ESM-LR	2034	2028	2064	2044	NA	2067
HIRHAM5	ICHEC-EC-EARTH	2032	2028	2054	2043	NA	2065
WRF331F	IPSL-IPSL-CM5A- MR	2023	2021	2042	2035	NA	2054
RACMO22E	ICHEC-EC-EARTH	2032	2026	2056	2042	NA	2065
RCA4	CNRM-CERFACS- CNRM-CM5	2035	2029	2057	2044	NA	2067
	ICHEC-EC-EARTH	2033	2026	2056	2041	NA	2066
	IPSL-IPSL-CM5A- MR	2023	2021	2042	2035	NA	2054
	MOHC-HadGEM2- ES	2021	2018	2037	2030	2069	2051
	MPI-M-MPI-ESM- LR	2034	2028	2064	2044	NA	2067

Table 2 - Annex I: List of models used in this atlas.

These two RCP scenarios provided a baseline scenario in which emissions peak around 2040 (RCP4.5) and a worst-case scenario with increased emissions throughout the 21st century (RCP8.5). For each model and scenario combination, also three global warming levels were considered (1.5 °C, 2.0 °C and 3.0 °C higher than pre-industrial conditions).

All RCMs had runs representing the historical climate and going up in the 21st century. The historical climate runs have biases when compared to the actual observations. In addition, a historical run is not necessarily synchronized with the actual years (i.e. 2003 of the RCM cannot be compared to the 2003 of reality), and thus cannot be compared to impacts in specific years. For these reasons, use was made of a delta-method approach to assess future drought risks in Europe.

For this, a recalibration was carried out using only standardised indices. These standardised indices were based on the historical runs, with the same levels applied to the future runs of a specific RCM (thus showing changes in the future). Because of the standardised nature of these indices, the newly calibrated thresholds (from the decision trees) for these standardised indices could be applied on the RCM indices regardless of any bias in the mean or variance, since these were encapsulated in the standardised indices. As such, it was possible to apply the newly calibrated trees to RCM historical and future runs to determine the change in likelihood of drought events in the form of ratios. This change in likelihood could subsequently be presented and applied to AAL and PML under current conditions to derive this two metrics under projected climate conditions.

Limitations of the quantitative risk assessment methodology

By clustering NUTS regions based on a similar sector-specific vulnerability, hazard indices were linked with proxies for direct impacts in each cluster to quantify the stressor-response link. This link was used as the vulnerability factor in the risk equation, thereby helping the selection of relevant proxies for vulnerability per sector, per region.

For some clusters of sectors, there was a low signal in the data-driven assessment as the machine learning algorithms were not sufficiently able to connect hazard indices with observed impacts. There may be multiple reasons for this:

(i) Some impact datasets were rather short, thus containing only a few drought episodes with potential impact. This creates the risk of overfitting the model to the specific drought conditions of the more recent years, hence not capturing well the effects of previous droughts. Ideally, impact datasets should be at least 30 years long, as is the case with the Eurostat maize production data, for example. Better impact databases can improve the reliability and precision of the risk assessment.

(ii) The spatial resolution of some impact datasets was rather low. Omitting the internal heterogeneity of meteorological or hydrological conditions might result in averages that do not reflect the extreme situations well, and hence lead to lower accuracies. Ideally, impact datasets should be at NUTS-3 level or even more detailed.

(iii) The hazard-impact link was assumed to be static, while it is known that agricultural water management, hydropower management and water supply techniques, for example, have changed over the past decades. Also, national regulations regarding priority water use might have shifted.

(iv) Some impact datasets did not have data for the whole of Europe. The vulnerability clustering approach overcomes this to some degree, but large vulnerability clusters omit internal heterogeneity (or other relevant factors influencing the hazard-impact link), while small vulnerability clusters might result in not having any impact evidence for a vulnerability cluster, and hence fail to capture the risk for this cluster. Ideally, there should be a good spread (regionally, or a good representation of all subsystems) in the impact dataset, as is the case with the Agri4Cast wheat production data, for instance.

(v) All impact datasets represented variability rather than observed drought-induced loss. In such cases, negative anomalies in sector productivity might have been caused by shocks/ trends other than droughts. To overcome this potential issue, models were trained to optimise precision (the model does not need to capture all impacts but should not predict impacts when none are present). A good example of a more focused impact is the nuclear power impact dataset that reports losses due to environmental conditions rather than just variability in production.

With respect to the sectors addressed in this atlas, it was difficult to get a good stressor-response link for river transportation in particular. This was probably due to the analysis level (national, because of the resolution of the impact data) and the level at which inland waterway transportation manifests itself on the ground: it is closely connected to the situation in very local bottleneck points. Instead, water supply is a system where the hard-impact link can be biased, as demand for water plays an important role when it comes to water abstraction. Abstraction may actually increase during dry periods but decreases when drought becomes very severe and rationing of water resources occurs. For hydropower, it became clear that the variability of hydropower is affected by many more factors (e.g. demand or market-driven ones) and drought only captures a part of that total variability.

Annex II
Analysed systems - data

Data Type	Data	Source	Agriculture	Terrestrial ecosystems	Water supply	River transportation	Energy	Aquatic ecosystems
Hazard	Precipitation	ERA5 https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5	x	x	x	x		x
	Potential evaporation	ERA5 https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5	x	x	x	x		x
	Temperature	ERA5 https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5						
	Soil moisture	EDO factsheet_soilmoisture.pdf (europa.eu)	x	x	x			x
	Streamflow	Lisflood https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_lowflowindex.pdf	x	x	x	x		x
	Total water storage	Grace https://grace.jpl.nasa.gov/						
Exposure and Impact	Crop yields	Eurostat (https://ec.europa.eu/eurostat/cache/metadata/en/apro_cp_esms.htm	x					
	Wheat yields	Agri4Cast (https://agri4cast.jrc.ec.europa.eu/dataportal/	x					
	Net primary production	MODIS (https://lpdaac.usgs.gov/products/mod17a3hgfv006/)		x				x
	Water abstraction	Eurostat (https://ec.europa.eu/eurostat/databrowser/product/page/env_watabs_rb)			x			
	Goods transported	Eurostat (https://ec.europa.eu/eurostat/cache/metadata/en/iww_go_q_esms.htm) and (https://ec.europa.eu/eurostat/databrowser/product/page/iww_go_actygofl)				x		
	Amount of hydropower produced per country	International Energy Agency (https://www.iea.org/data-and-statistics/data-tools/monthly-electricity-statistics)					x	
	Direct nuclear power outage caused by	Power Reactor Information System (pris.iaea.org/pris /)					x	
	Forest map	CORINE “Forest” class https://land.copernicus.eu/pan-european/corine-land-cover		x				
	Wetland sites	CORINE “Inland wetland” class https://land.copernicus.eu/pan-european/corine-land-cover						x
Vulnerability	Tree species map	Brus, D.J., G.M. Hengeveld, D.J.J. Walvoort, P.W. Goedhart, A.H. Heidema, G.J. Nabuurs, K. Gunia, 2011. Statistical mapping of tree species over Europe. Special Issue European Journal of Forest Researchs		x				x
	Ecological zones	European Environmental Agency Digital map of European ecological regions https://www.eea.europa.eu/data-and-maps/data/digital-map-of-european-ecological-regions)		x				x
	GDP	Eurostat (https://ec.europa.eu/eurostat/databrowser/view/nama_10r_2gdp/default/table?lang=en)			x	x	x	
	Aridity index	Zomer & Trabucco (2022) (https://www.nature.com/articles/s41597-022-01493-1)			x	x	x	
	Government Effectiveness	EQI index, (Charron et al. 2021) (https://www.gu.se/en/quality-government/qog-data/data-downloads/european-quality-of-government-index)			x	x	x	
	Admin boundaries	National boundaries (for Nuclear)					x	
	Agro	FAO (https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/7a10de20-7845-453d-8af9-90688ef5b0f9)	x	x				x
	Share of arable land that is irrigated	Euostat (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_irrigation)	x					
	Available Water Capacity of the soil	ESDAC (https://esdacviewer.jrc.ec.europa.eu/layers/geonode%3Aawc_top	x					
	Soil compaction	ESDAC (https://esdac.jrc.ec.europa.eu/themes/soil-compaction)	x					
	Maximum Yield	Eurostat (https://ec.europa.eu/eurostat/cache/metadata/en/apro_cp_esms.htm	x					

Table 1 - Annex II: Summary of data used for the data-driven analysis, with links to sources. Exp for exposure

Drought hazard variables

The same hazard input variables were used for all the systems. These variables are summarised in the two tables below for the current climate and for the assessments of the future, respectively. For future drought risk, only standardised variables were used (and not the absolute and relative variables) as biases in mean and variance (which exist in the projected scenarios) do not affect standardised indices.

These hazard variables were aggregated to the spatial level at which the impact data were available for use in the decision trees (NUTS-3, NUTS-2, national). In addition, for some systems, exposure data were used to select in more detail the cells to use for spatial aggregation of the hazard data to the NUTS level. This was particularly the case for agriculture and for the terrestrial and freshwater ecosystems, using the relevant Corine Land Cover (CLC) classes.

Inputs	Source current	Temporal aggregation	Derived indices*
Precipitation Evapotranspiration Temperature	(ECMWF) ERA5, 30 km spatial resolution	1, 3, 6, 12 months	SPI, SPEI, SETI, SEI T%,P%, PET%, Pr-ET% Psum, ETsum, Tmean
Soil moisture and streamflow	EDO/GDO repository, output of the LISFLOOD model	1, 3, 6, 12 months	SSMI, SSFI Q%, Q-min%, SM% Q-min, SMInx, SMIan

** Standardised indices are based on: SPI: precipitation; SPEI: precipitation - potential evapotranspiration; SETI: precipitation / potential evapotranspiration; SEI: potential evapotranspiration; SSMI: soil moisture; SQI: streamflow (Q). Relative indices represent the (monthly) relative difference to the median (set at 100%). Absolute indices refer to sum, mean or minimum of the input (per month). For streamflow (Q-min) the minimum discharge of the pixel with the highest mean of the spatial unit (e.g. the outflow point) was taken. SMInx refers directly to the soil moisture index, and SMIan to the anomaly therein.*

Table 2 - Annex II: Hazard indices used in the analysis for current climate conditions.

Inputs	Source projected	Temporal aggregation	Derived indices*
Precipitation Evapotranspiration Temperature	11 EURO CORDEX models, 2 RCP scenarios (RCP 4.5 and RCP 8.5)	1, 3, 6, 12 months	SPI, SPEI, SETI, SEI
Soil moisture and streamflow		1, 3, 6, 12 months	SSMI, SSFI

Table 3 - Annex II: Hazard indices used in the analysis for projected climate conditions.

Future changes in hazard

To assess drought risk under future climate conditions, an ensemble of 11 regional climate models from EURO-CORDEX was explored. Two representative concentration pathways (RCPs) were considered for each model: RCP4.5 (intermediate) and RCP8.5 (worst-case). For each model and scenario combination, three global warming levels were also considered (+1.5°C, +2.0°C and +3.0°C compared to pre-industrial conditions). See Annex I for more details. Here results are shown for the three warming levels, which combine the various climate model results for both RCP scenarios.

The maps show the average changes in the hazard indices throughout the year , compared to the historical conditions (1981-2010) for different warming levels. For the future climate projections, only standardised indices were used in order to avoid biased outcomes. The maps below give examples of the changes in the mean standardised precipitation index (SPI), the standardised precipitation evapotranspiration index (SPEI; precipitation minus evapotranspiration), the standardised soil moisture index (SSMI) and the standardised streamflow index (SQI). All the maps show averages over 30 years, and indices for two different accumulation periods (1 and 6 months) are used to illustrate these. For each warming level, data from both the RCP 4.5 and the RCP 8.5 RCM run were taken to calculate the average. Thus, they represent the averages of 22 runs (11 models, 2 RCP scenarios). However, the average +3 °C warming level is based on fewer runs, as not all the RCP 4.5 runs result in a warming of 3 °C (there is not enough data for the years around the +3 °C level to establish the 30-year average).

Different types of indices are relevant for different systems and impacts. For instance, shipping is very strongly associated with short term discharge fluctuations (e.g. SQI1), whereas agriculture and ecosystems seem to be strongly related to medium scale precipitation and evapotranspiration indices. The results of the data-driven analysis shows that soil moisture indices were not often used in the decision trees (presumably because SPEI type indices are already a good indication for that). Nevertheless, results for SSMI are also shown. Note that given the nature of the standardized indices, the historic conditions are always as good as zero as the average of a standardized metric should be zero.

All the maps show a clear north-south gradient when it comes to how mean drought indices change moving into the future, (as was also confirmed in the last IPCC synthesis report). The Mediterranean area sees a clear increase in drought hazard with more negative standardised index values. Central Europe either sees a (slight) increase or little change. More positive values are seen for northern Europe (Scandinavia and Baltic states) when it comes to the average drought indices. This contrast in changes between the north and south of Europe becomes more pronounced with higher warming levels. Please note that the figures show the average values of drought hazard indices. However, the changes in variance are also significant, and the climate models generally show higher variance for the future. This may further worsen the situation in the Mediterranean area, and may result in increases in drought impacts, even if average index values remain similar or even improve.

Standardised precipitation index (SPI)

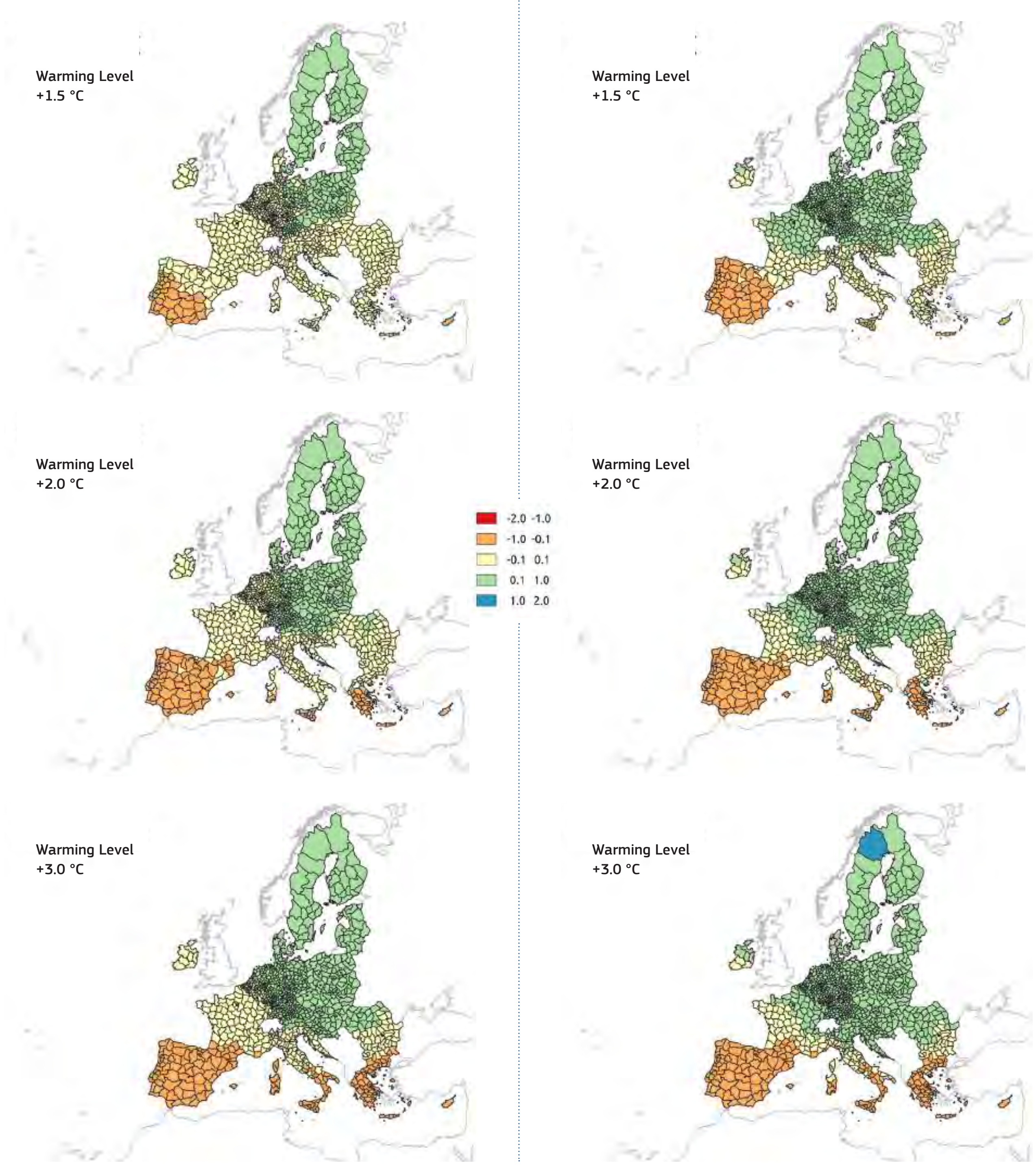

Figure 67

Evolution of the standardised precipitation index (SPI) with accumulation periods of 1 (left) and 6 (right) months for different warming levels (WLs), considering RCP 8.5 and RCP 4.5 together.

Standardised index for precipitation minus evapotranspiration (SPEI)

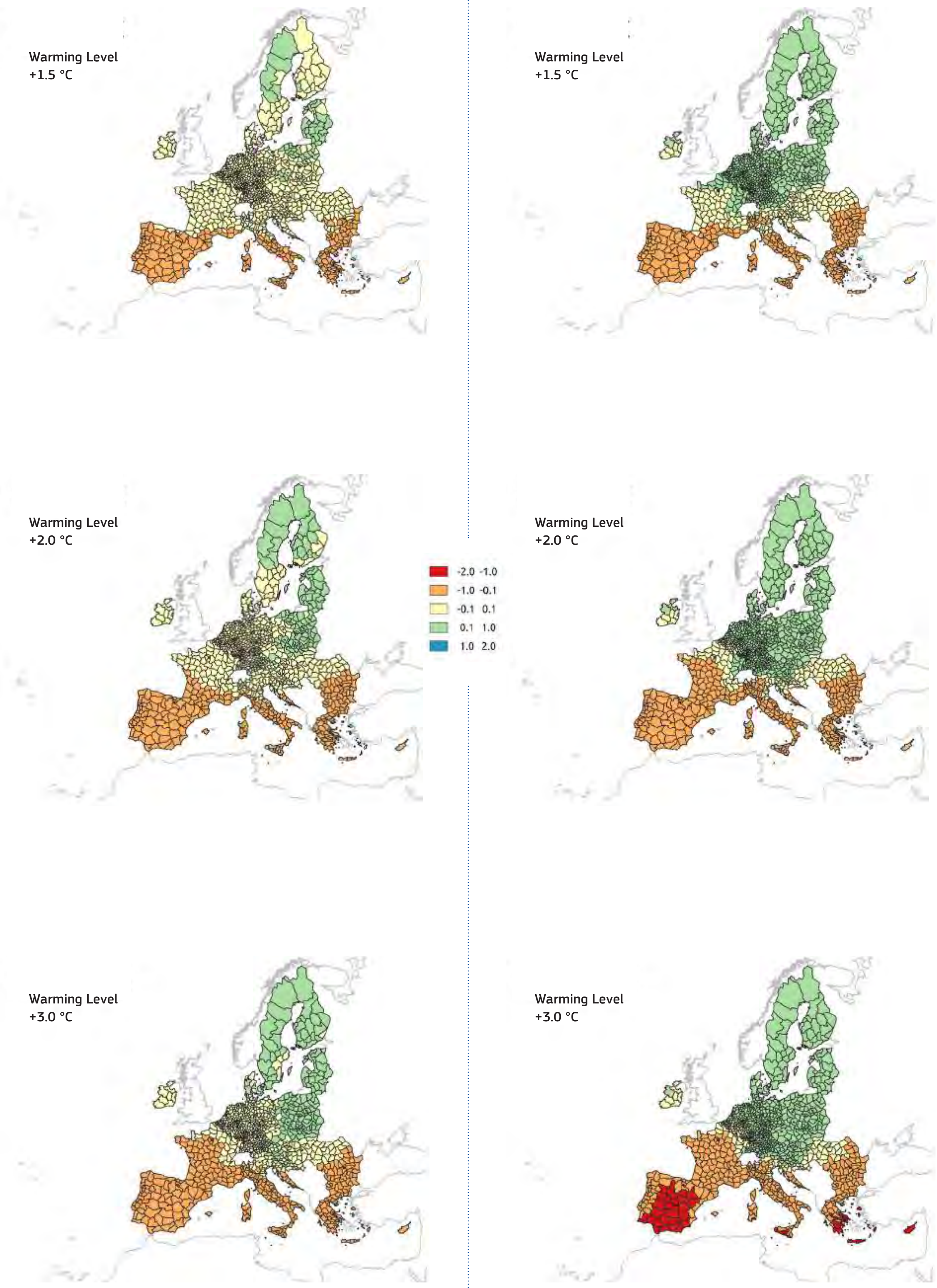

Figure 68

Evolution of the standardised index for precipitation minus evapotranspiration (SPEI) with accumulation periods of 1 (left) and 6 (right) months for different warming levels (WLs), considering RCP 8.5 and RCP 4.5 together.

Standardised soil moisture index (SSMI)

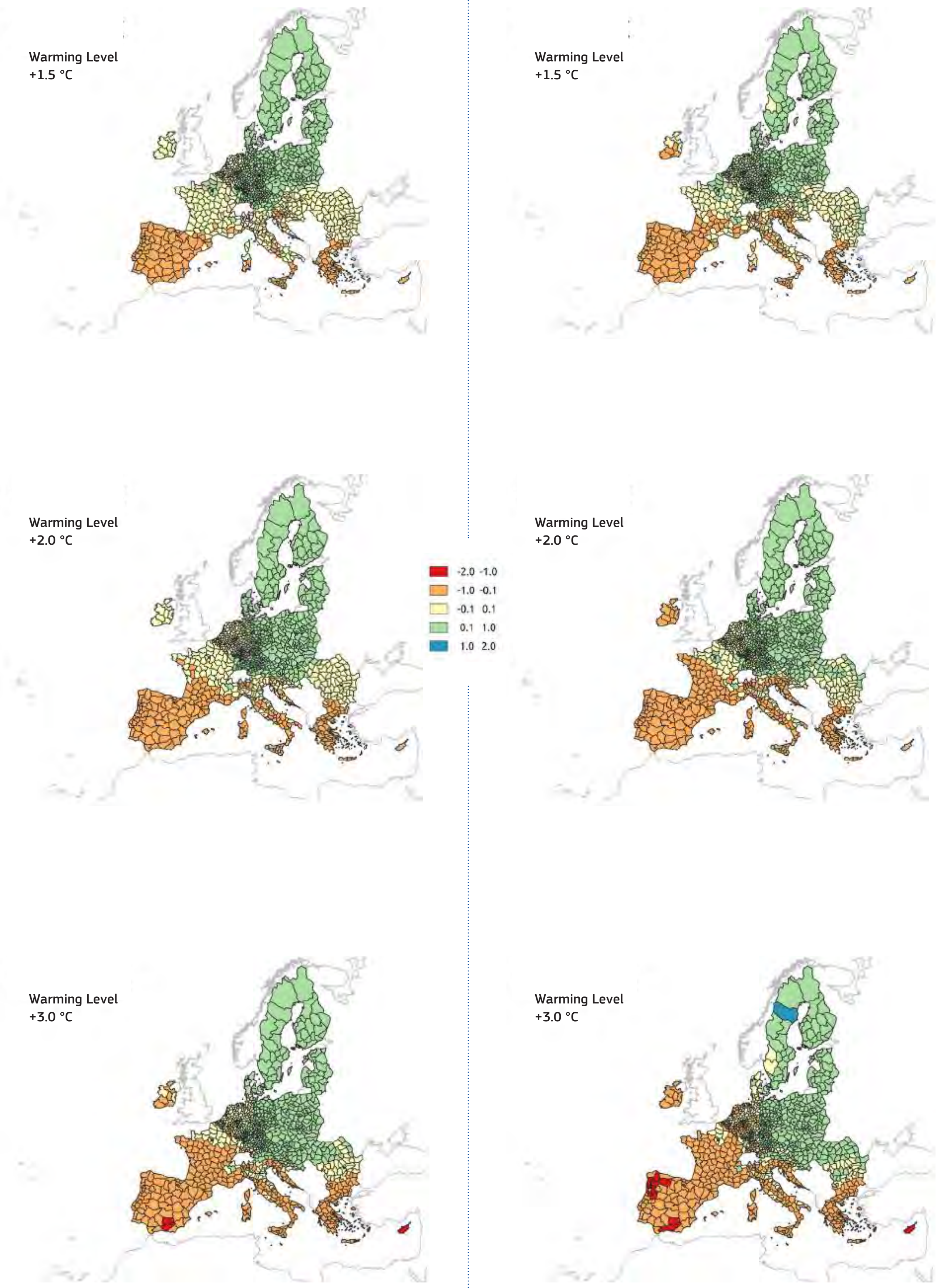

Figure 69

Evolution of the standardised soil moisture index (SSMI) with accumulation periods of 1 (left) and 6 (right) months for different warming levels (WLs), considering RCP 8.5 and RCP 4.5 together.

Standardized streamflow index (SQI)

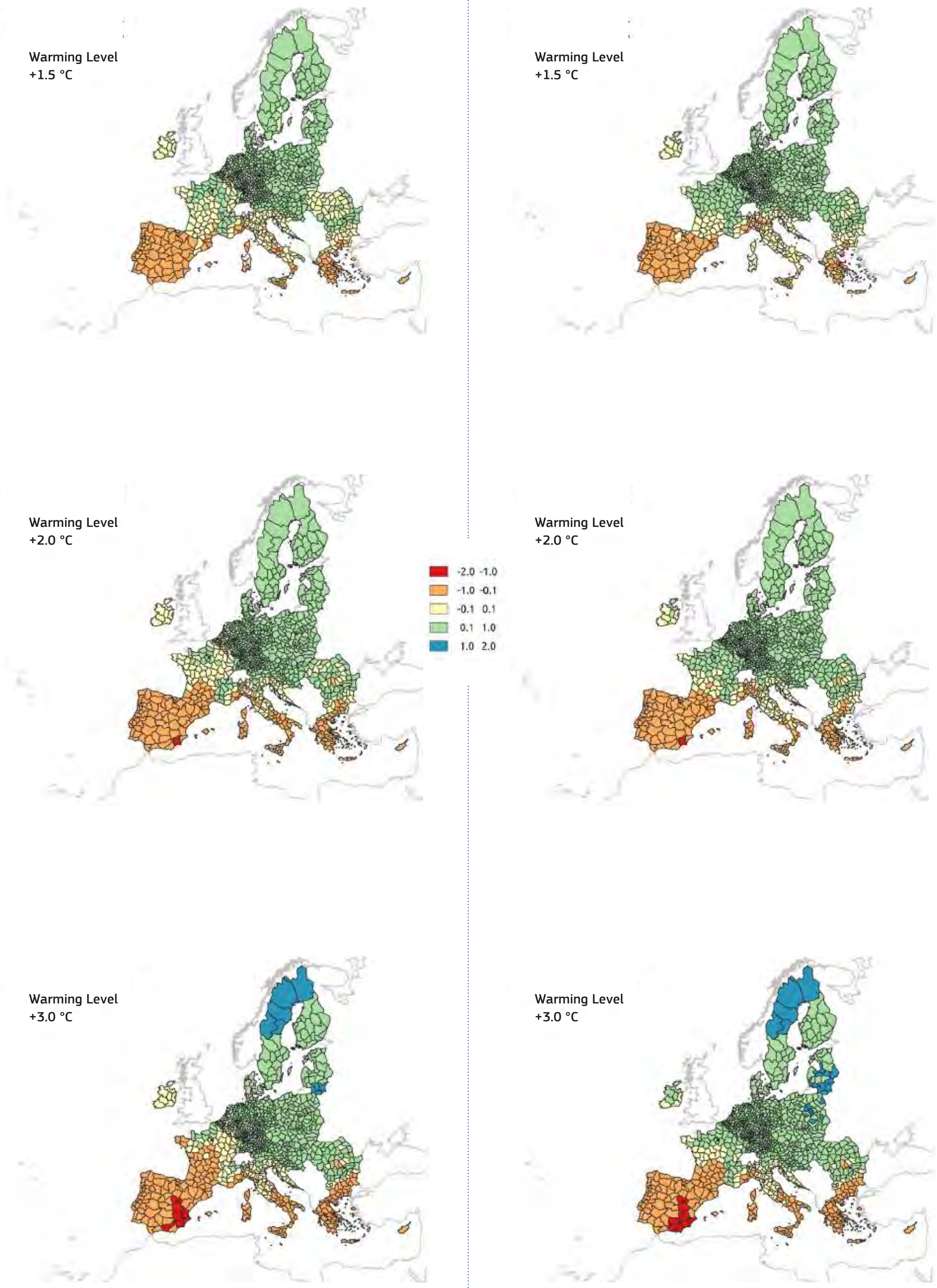

Figure 70

Evolution of the standardised streamflow index (SQI) with accumulation periods of 1 (left) and 6 (right) months for different warming levels (WLs), considering RCP 8.5 and RCP 4.5 together.

Agricultural System

Impact data

We used the following data on annual crop yield (t/ha = harvested tonnes divided by harvested area in hectares) to evaluate the observed drought-induced losses in agricultural production:

- Eurostat data on historical (1979-1999) crop production and on crop production in national humidity (2000-2021) at NUTS-2 level[1] (except for France and Germany), for four different crops: maize, barley, potato, rice.
- JRC Agri4Cast data (1979-2017), containing harmonised subnational data on wheat crops collected for the EU by the national statistical institutes and the Eurostat REGIO DB: soft, durum and total wheat.

Exposure data

The CORINE Land Cover map of Europe (2018) from the European Environment Agency, based on remote sensing technologies, was used to evaluate the cropland area (arable land and permanent crops) exposed to droughts. In addition, average production (yield, t/ha) exposed to droughts was derived from the Eurostat database.

Data on crop yields, identified by the impact chains as the main variable impacted by drought, were collected from Eurostat (1975-2021) and from the JRC Agri4Cast database (1981-2019). The analysis was conducted at NUTS-2 level on five crops: wheat (total of soft and durum), maize, barley, potato, rice.

Exposure, i.e. the system elements that could be adversely affected by the drought hazard, is generally represented using the average crop production of the last five years, where data were available.

Maps showing vulnerability clusters are featured further below.

Vulnerability data

Candidate vulnerability layers were selected based on the information derived from impact chain models for this sector and included:

- Agro-ecological zones map as a proxy for the climate zones (GAEZ map v4 of FAOSTAT[2]).
- The available water capacity of the soil as a proxy for root depth and drainage (high/low; based on AWC data from ESDAC data[3]).
- Soil compaction as a proxy for tillage practices (high/low; based on ESDAC data[3]).
- The average yield of each region as a proxy for yield potential (high/low).
- The share of irrigated arable land in order to differentiate irrigated production from rain-fed production, for crops where both are possible (Eurostat data[4]).

Overall, the vulnerability layers used per crop type are shown in Table 4. Maps also show these vulnerability clusters further below.

	Agro-ecological zones	AWC (H/L)	Soil compaction (H/L)	Average Yield (H/L)	Irrigated/ rainfed (Ir/Rf)
Wheat		x	x	x	x
Barley		x	x	x	x
Maize	x	x	x	x	x
Potato	x	x	x	x	x
Rice	x				

Table 4 - Annex II: Composition of vulnerability clusters used in the data-driven analysis.

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[1] *Nomenclature of territorial units for statistics (NUTS) is a hierarchical system for dividing up the economic territory of the EU and the UK. NUTS 2 generally corresponds to the administrative divisions of the EU member states, regions or provinces, depending on the country.*

[2] *https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/7a10de20-7845-453d-8af9-90688ef5b0f9*

[3] *https://esdac.jrc.ec.europa.eu/content/topsoil-physical-properties-europe-based-lucas-topsoil-data*

[4] *https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_irrigation*

Wheat

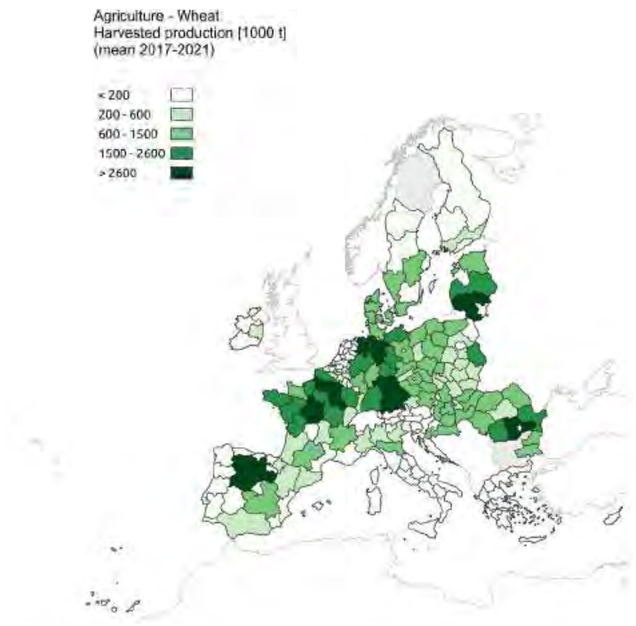

Figure 71

Wheat exposure. Average harvested production 2017-2021 at NUTS-2 level and NUTS-1 level for Germany (source: Agri4Cast and Eurostat).

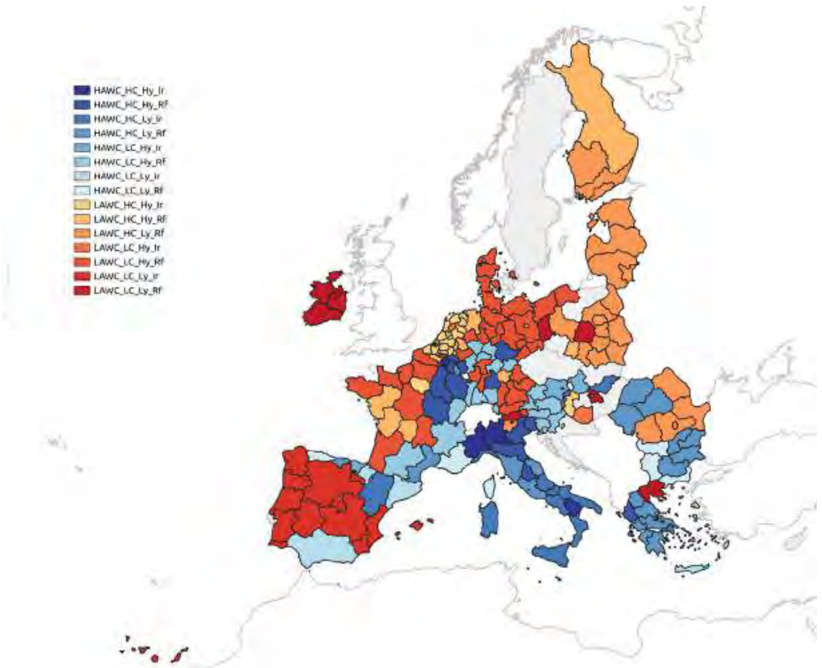

Figure 72

Vulnerability clusters for wheat based on Available Water Capacity (High; Low), Soil Compaction (High; Low), Average yield (High; Low) and Irrigated/Rainfed (Ir; Rf).

Barley

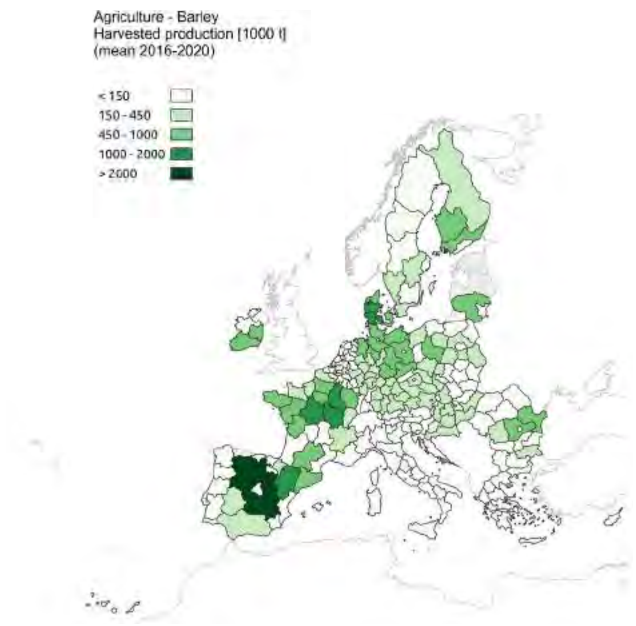

Figure 73

Barley exposure. Average harvested production 2016-2020 at NUTS-2 level and NUTS-1 level for Germany (source: Eurostat).

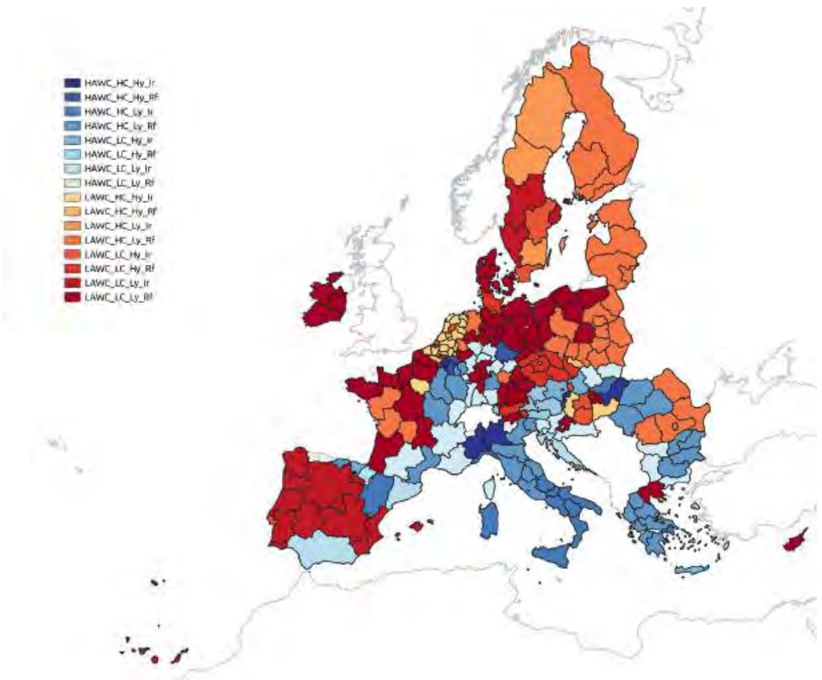

Figure 74

Vulnerability clusters for barley, based on: available water capacity (high; low), soil compaction (high; low), average yield (high; low) and irrigated/rain-fed (Ir; Rf).

Maize

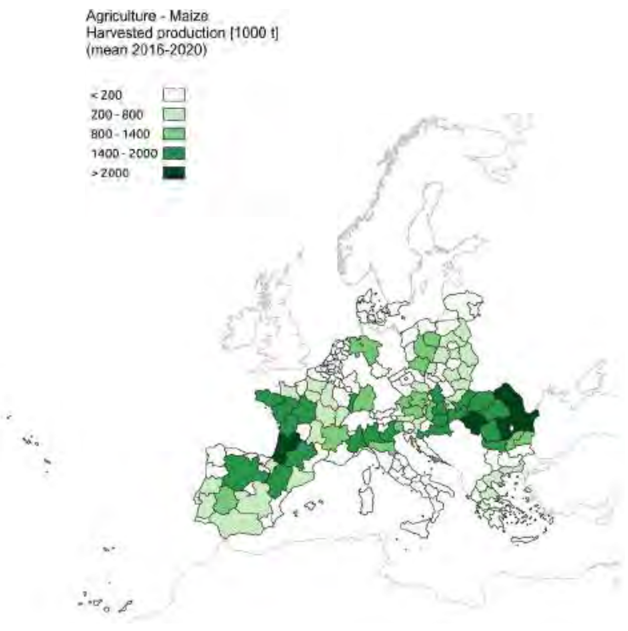

Figure 75

Maize exposure. Average harvested production from 2016 to 2020 at NUTS-2 level (source Eurostat) and NUTS-1 level for Germany (source Eurostat).

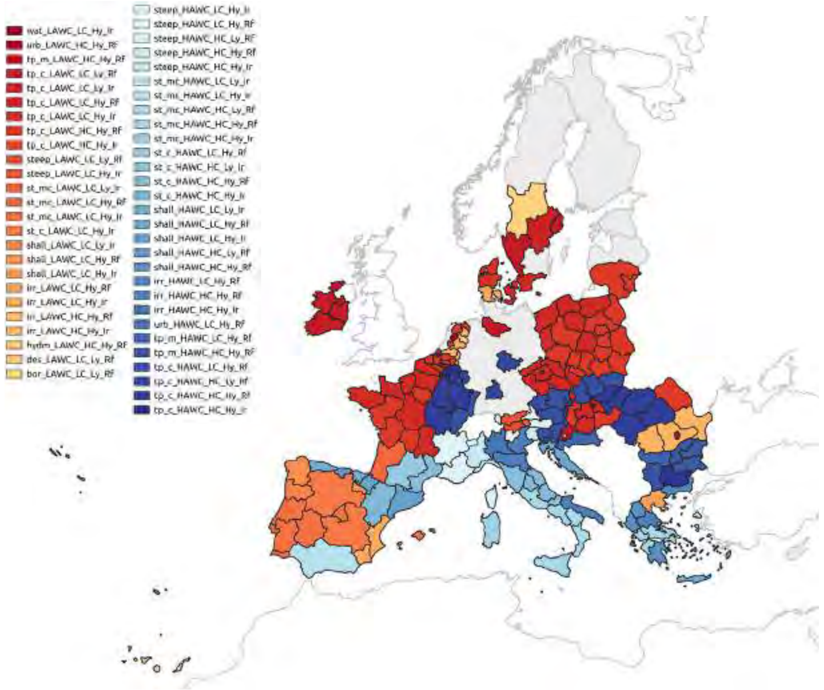

Figure 76

Vulnerability clusters for maize based on: agro-ecological zones (bor=boreal/cold climate; des=desert/arid climate; hydm=dominantly hydromorphic soils; irr=land with ample irrigated soils; shall=land with severe soil/terrain limitations; st_c=sub-tropics, cool; st_mc=sub-tropics, moderately cool; steep=dominantly very steep terrain; tp_c=temperate, cool; tp_m= temperate, moderate; urb=dominantly built-up land; wat=dominantly water), available water capacity (HAWC=high; LAWC=low), soil compaction (HC=high; LC=low), average yield (Hy=high; Ly=low), and irrigated(Ir)/rain-fed (Rf).

Potato

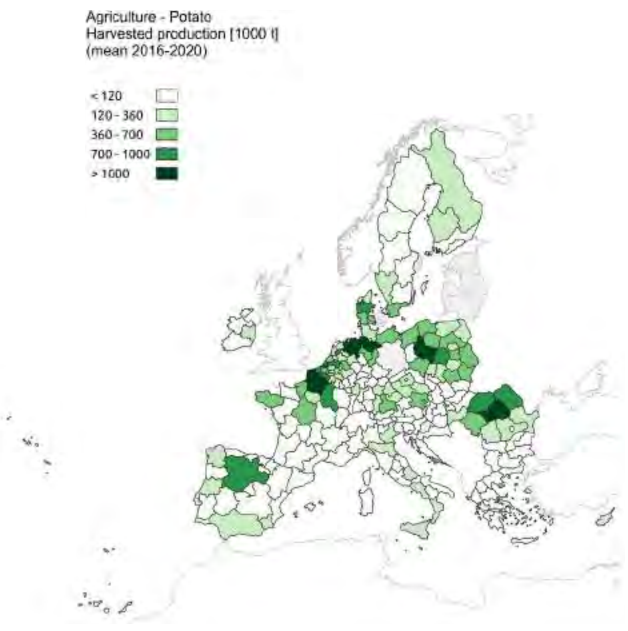

Figure 77

Potato exposure. Average harvested production 2016-2020 at NUTS-2 level (source: Eurostat).

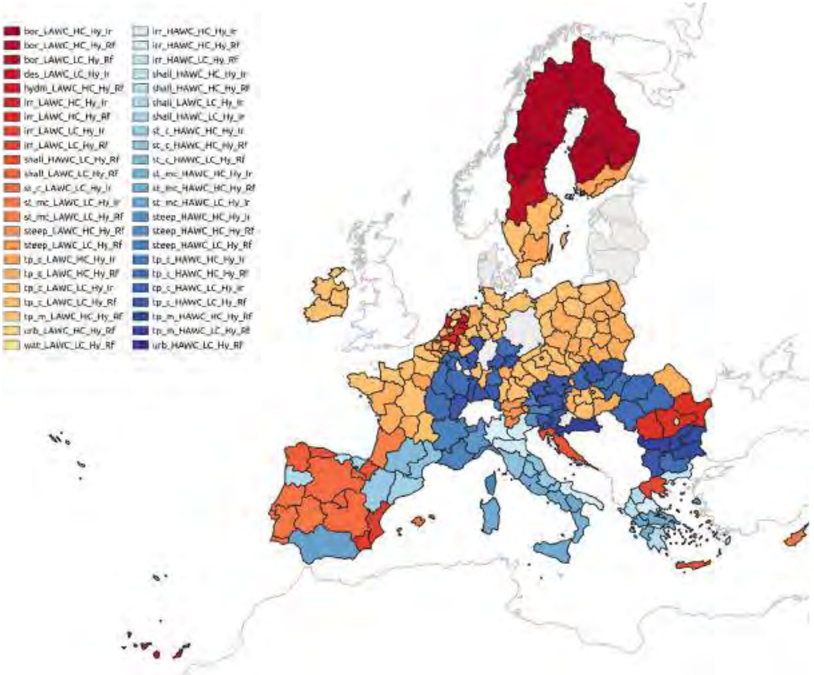

Figure 78

Vulnerability clusters for potato based on: agro-ecological zones (bor=boreal/cold climate; des=desert/arid climate; hydm=dominantly hydromorphic soils; irr=land with ample irrigated soils; shall=land with severe soil/terrain limitations; st_c=sub-tropics, cool; st_mc=sub-tropics, moderately cool; step=dominantly very steep terrain; tp_c=temperate, cool; tp_m= temperate, moderate; urb=dominantly built-up land; wat=dominantly water), available water capacity (HAWC=high; LAWC=low), soil compaction (HC=high; LC=low), average yield (Hy=high; Ly=low), and irrigated(Ir)/rain-fed.

Rice

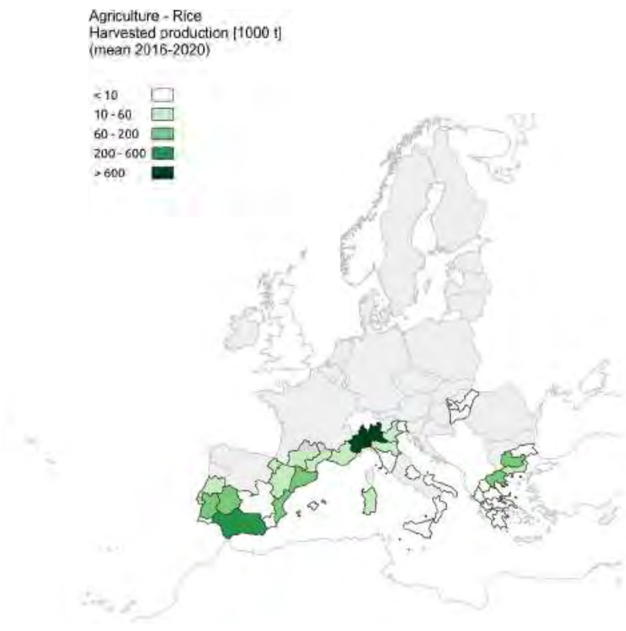

Figure 79
Rice exposure. Average harvested production 2016-2020 at NUTS-2 level
(source: Eurostat).

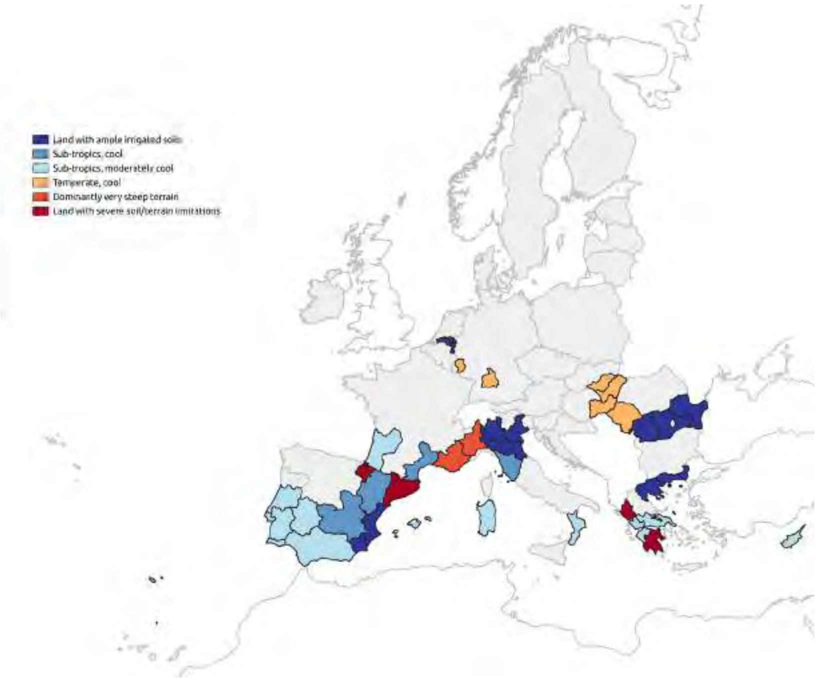

Figure 80
Vulnerability clusters for rice based on agro-ecological zones.

Water Supply

Impact data

As impact proxy for losses in water supply, Eurostat data on the annual renewable freshwater resources for each river basin district (RBD) were used, more specifically, water abstraction for public water supply in million cubic meters per year at an RBD-level (ENV_WATABS_RB, Eurostat, 2022). This dataset provides an acceptable spatial coverage at NUTS-2 level. The temporal coverage is generally a period of 20 years, from 2000 to 2020, with the exception of some countries where data were available only for recent years (Spain) or others where records for recent years were not available (the Netherlands).

The RBD-based dataset was converted into a NUTS-based dataset, by computing the percentage area of each NUTS-2 region within a RBD and then resampling the amount of water abstraction for the significant area of a NUTS-2 region within each RBD.

The impact chains show that drought can result in: (i) high water demand; (ii) reduced water availability. This means that water abstraction can increase as a result of droughts (due to high water demand), and that water abstraction decreases when water rationing is enacted due to reduced water availability. This theoretical two-way relationship complicates the assessment of impact of drought on water supply when using water abstraction as a proxy for impact. Here, we used increased abstraction as an indicator of drought impact, following (i). The rationale is that this will happen earlier during a drought, while rationing happens later, and only if the drought is severe enough (Belleza et al. 2023). In such a situation, the increased abstraction is likely to have already occurred, and, whilst rationing may still take place, the cumulative amount of water abstracted will nevertheless be higher, due to the higher demand earlier in the drought. In such situations the increased abstraction is likely to have occurred already, and while rationing may take place, the cumulative amount of water abstracted will still be higher due to the higher demand earlier during drought.

Exposure data

The exposure parameter for the water supply sector is the average annual water abstraction for public water supply by river basin district. This value was determined by taking the average value for the last five years (ignoring missing data values). The period of the last five years was chosen to avoid going back too far in time and thus having changing baselines connected with economic development and demographic growth.

Vulnerability data

Water abstraction is considerably dependent on national policy, which regulates where, when and how much water may be abstracted. However, given the relatively limited amount of impact data for water supply, pooling only nationally would have resulted in insufficient data for training the algorithm. Therefore a middle ground was chosen and a vulnerability cluster consisting of four regions was used. This was carried out using the four sub-regions for Europe as defined by the UN Geoscheme (see UNSD - Methodology).

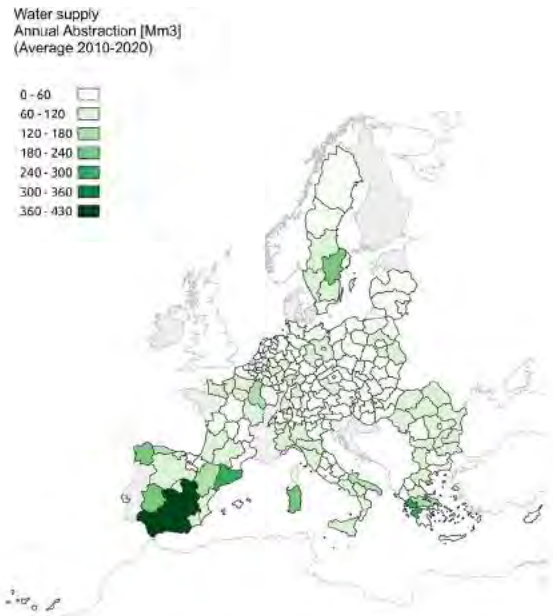

Figure 81

Average annual water abstraction for public water supply (reference period 2010-2020). The analysis was conducted at NUTS-2 level for those territorial units with sufficient data for computation.

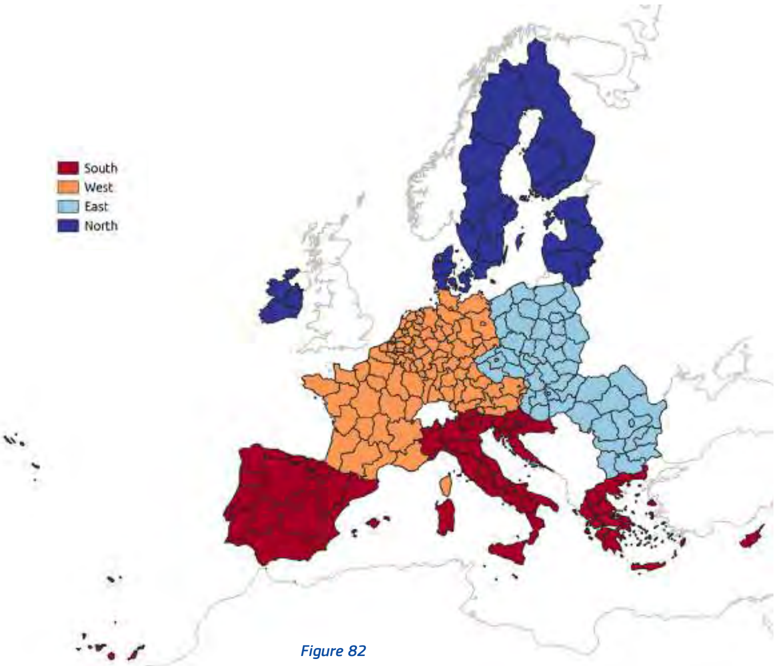

Figure 82

Vulnerability clusters for water supply based on EU Regions.

Energy Production

Impact data – Hydropower

The drought-induced impact on hydropower energy production was evaluated by using the amount of hydropower produced per country (NUTS-0 level) per year. The dataset "monthly electricity statistics" is freely available, updated monthly and starts from 2010. The data on hydropower production were collected on 17 June 2022.

Impact data – Nuclear power

For losses in nuclear power generation, information was gathered from the Power Reactor Information System (PRIS) statistics. This is a database from the International Atomic Energy Agency and monitors in detail the production and outages of individual nuclear plants in associated partner countries. Specifically, the direct outage caused by "Environmental conditions" (lack of cooling water due to dry weather, cooling water temperature limits, flood, storm, lightning, etc.) was extracted. The reports give total energy loss in GWh. Please note that the environmental conditions are not limited to dry weather, but also other hazards, most notably cooling water temperature limits. Since drought conditions in Europe often coincide with periods of high temperatures, we expect strong correlation here. Data for the reactors were retrieved for the years 2004-2021 and aggregated to NUTS-2 level. In total, this resulted in 35 NUTS regions with data.

Since the PRIS data directly reflects losses, as opposed to using a production time series, a slightly different approach was used in preparing the impact/exposure data for the drought analysis. Here, we determined the actual Gwh produced per reactor per year and added the total outage (in GWh) due to all causes (including the environmental conditions). This was taken as the baseline of what the nuclear power plant would produce. Then the outage due to environmental conditions was translated into a percentage of this baseline production and considered as the loss for that year.

Exposure data

For hydropower, the exposure per NUTS-0 region was calculated by averaging the amount of power produced in GWh at a country level over the last five years of available data (2017-2021).

For nuclear power, exposure was shown through the average baseline power production (produced GWh plus total of all outages) per NUTS-2 region, again based on the last five years of available data (2017-2021).

Vulnerability data

For hydropower, three general vulnerability indicators had a good spatial reach (NUTS-2 level, with no missing data) and these represent vulnerability from three relevant but broad domains in determining drought vulnerability:

- Gross domestic product expressed in purchasing power standards (GDP in PPS) at current market prices per capita (in million euros) was used to enable an up-to-date comparison between NUTS-2 regions to account for economic vulnerability (NAMA_10R_2GDP; Eurostat 2022). This was a proxy for how strongly other financial shocks might influence the hazard-impact link.
- Government effectiveness (EQI 2021 data from Charron et al. 2022) was used to incorporate political vulnerability. This was a proxy for how fast a government can change its policies regarding water use and water abstractions in the face of an upcoming or ongoing drought.
- Aridity index (AI, data from Zomer et al. 2022) was used for biophysical vulnerability. This was a proxy for the overall water availability in a region, which influences the space for options in water abstractions. This gridded database was resampled to average values per NUTS-2 region.

For the assessment of drought impacts on hydropower due to climate change, a change in clustering was needed. The reason for this was that the future simulations used fewer hazard indices (only the standardised ones), and more pooling of regions was necessary as a result, so as to obtain sufficient data and have reliable decision trees. Thus, they were pooled over four EU regions, using the four sub-regions as defined by the UN Geoscheme (see also here UNSD - Methodology).

For nuclear power, the individual reactors were clustered per country, considering that policy related to power generation and outage is similar within each country.

Hydropower

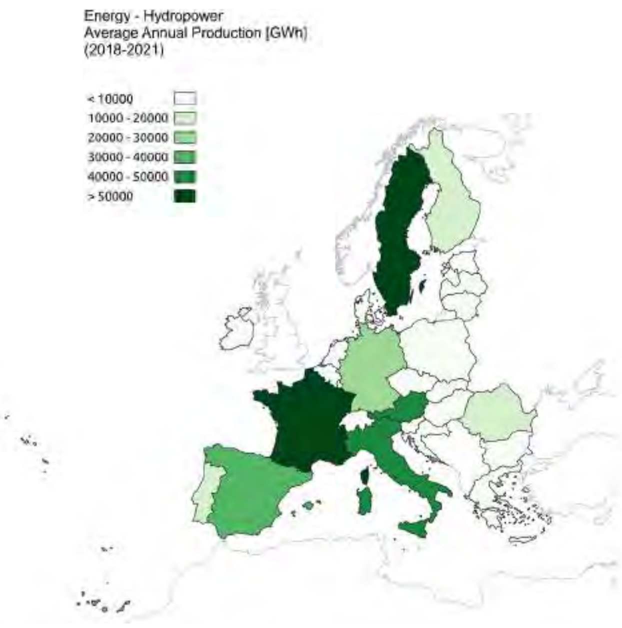

Figure 83
Average annual production in GWh at a national level (source: Eurostat; reference period: 2018-2022).

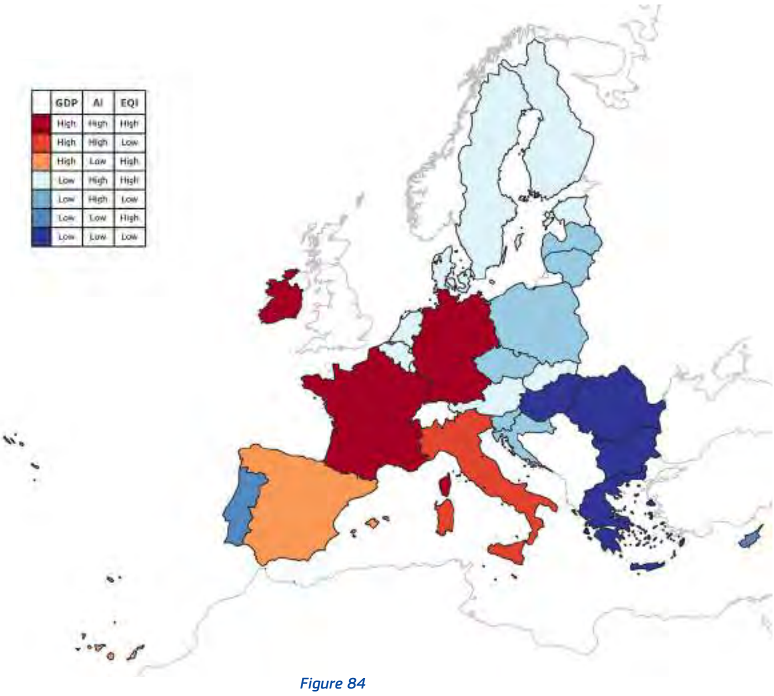

Figure 84
Vulnerability clusters used in the analysis of hydropower.
Legend: GDP (gross domestic product), EQI index (government effectiveness), AI (aridity index).

Nuclear power

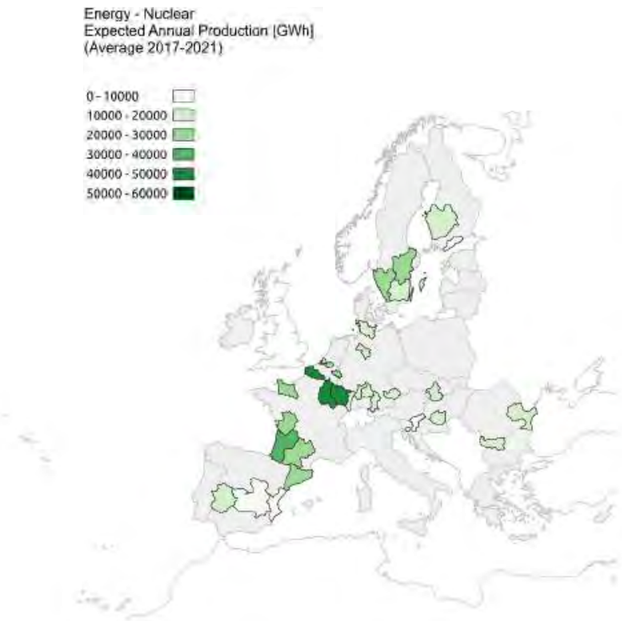

Figure 85
Average annual production in GWh at NUTS-2 level (source: Power Reactor Information System statistics; reference period: 2017-2021).

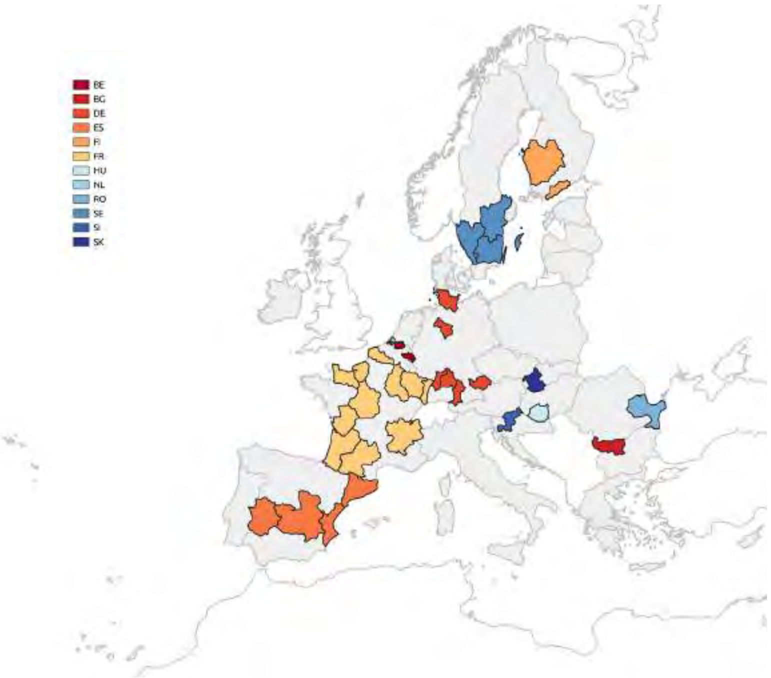

Figure 86
Vulnerability clusters (national clusters) used for the analysis of nuclear power.

River transportation

Impact data

Multiple drivers influence river transportation, ranging through physical, environmental and economic drivers. Eurostat's extensive database on transported goods on a pan-European scale was used in determining the influence of droughts on inland water transport. The most complete river transportation dataset from Eurostat is the "Transport by nationality of vessel [IWW_GO_QNAVE]" dataset, which contains data on a quarterly scale from 1982 until 2022 (with some data gaps). Nonetheless, only data from 2000 onwards were used because of the many data gaps before the year 2000. The data were aggregated from quarterly to yearly totals for the analysis.

Transport by nationality of vessel, at NUTS-0 (national) level, was thus the dataset used as impact input data. We focused this analysis on rivers with significant inland waterway shipping traffic, including the rivers Elbe, Meuse, Seine, Vistula, Rhine and Danube, and their connected canals. The analysis then focused on Germany, the Netherlands, Belgium, France, Poland, Austria, Croatia, Hungary, Slovenia and Romania. Please note that a reduction in transported goods could indirectly affect countries without inland waterways, due to the interruption of logistical chains.

Exposure data

The exposure parameter for the river transport sector was the amount of "Goods loaded by nationality of vessel" (Eurostat). Exposure per NUTS-0 region was calculated by averaging the amount of goods loaded over the last five years of available data, from 2018 to 2022.

Vulnerability data

Because of the complex interplay of river transport between countries and the transfer of risk between different regions and sectors, it proved difficult to determine accurate vulnerability values for this sector. In addition, drought impacts in upstream regions can have a profound effect downstream.

This interconnection between regions and drought impacts in terms of risk transfer led to the decision not to incorporate vulnerability values when determining the drought risk for river transport. Therefore, the data were not clustered and analysis was performed on national level (as impact data were available at country level only). This resulted in the clusters illustrated in Figure 88.

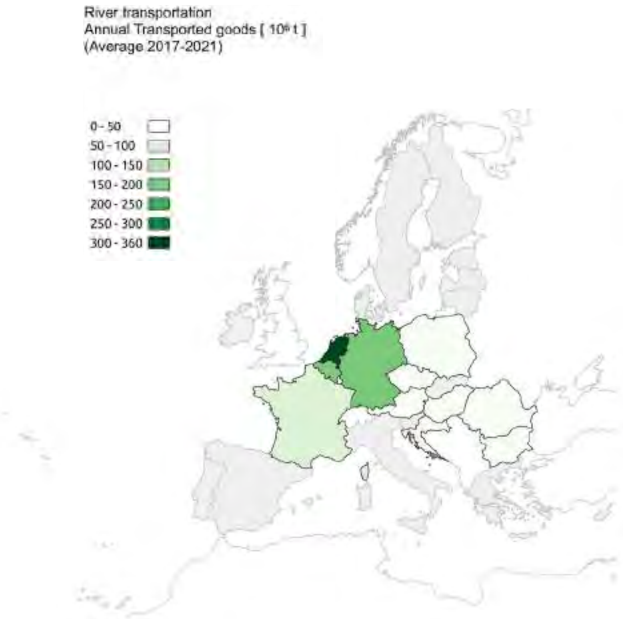

Figure 87

Average annual transported goods (reference period: 2017-2021) at country level (source: Eurostat).

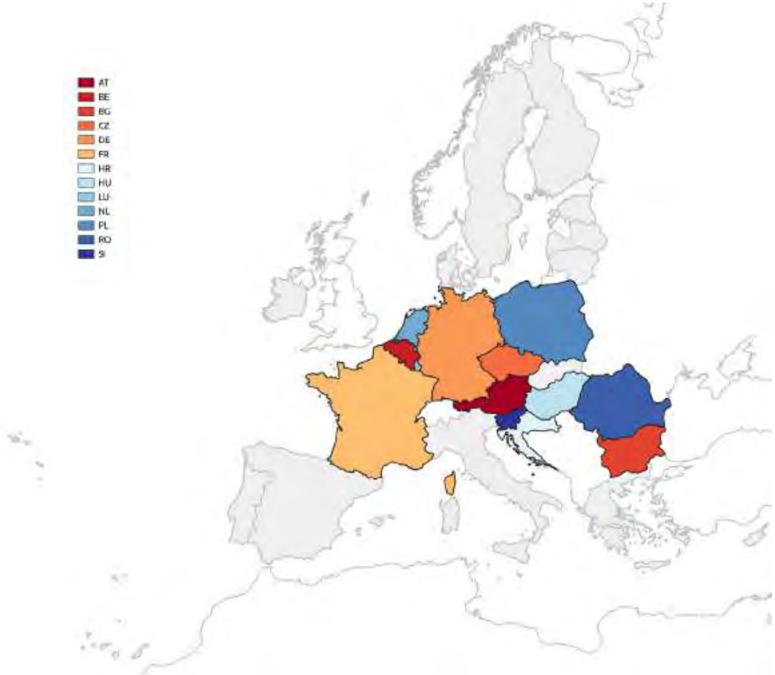

Figure 88

Vulnerability clusters (national clusters) used in the analysis for transportation.

Terrestrial and freshwater Ecosystems

Impact data

The parameter chosen to measure the loss in ecosystems due to droughts was net primary production (NPP), considered as the basis of all ecosystem services. Primary production is the entry point of energy and carbon into ecosystems. Net primary production is the amount of biomass or carbon produced by primary producers per unit area and time, obtained by subtracting plant respiratory costs (Rp) from gross primary productivity (GPP) or total photosynthesis.

Annual net primary production values at 500m spatial resolution were obtained from MODIS (MOD17A3HGF product). For wetlands, specific models applied to remote sensing data are often used, such as the Carnegie-Ames-Stanford Approach (CASA), which require several assumptions and do not necessarily apply to the wide range of wetlands considered here. To obtain a first expeditive estimate, we directly adopted the NPP product as provided by MODIS. Future studies may consider applications of models such as CASA.

Annual net primary production values were masked and spatially aggregated to NUTS-3 level for analysis. For terrestrial ecosystems, Corine Land Cover “forest” classes were used to compute area fraction images (% of forest or wetlands in original NPP 500m pixel resolution), while for wetlands the “inland wetland” classes were used. Only wetlands larger than 1 km^2 were considered.

Yearly Net Primary Production values were masked and spatially aggregated to NUTS-3 level for analysis. For terrestrial ecosystems Corine Land Cover “Forest” classes were used to compute area fraction image (% of forest or wetlands in the 500m NPP pixel), while for wetlands the “Inland wetland” classes were used. Only wetlands larger than 1 km^2 were considered.

Note: Initial analysis attempted to use the ACP forest health database and RAMSAR data on wetland. However, the former is too patchy (not covering enough regions) and of a short length for robust analysis. The latter provides a detailed exposure map but multiple errors and inconsistencies were found within, hence the choice for Corine as delineation.

Exposure data

Exposure of terrestrial and freshwater ecosystems was depicted using two maps. For the first, exposure was computed like for the other systems, as the average of the past few years and, in this case, the average annual net primary production (Kg*C/m^2; reference period: 2017-2022). Alongside, Corine Land Cover was used with the “forest” classes for terrestrial ecosystems, and the “inland wetland” class for freshwater ecosystems. This last exposure layer was used to weight the hazard indices when determining their values for the NUTS regions.

Vulnerability data

To define different groups with similar vulnerabilities for terrestrial (forests) and freshwater (wetlands) ecosystems, various options were tested out. These included agro-ecological zones, eco-zones, the water exploitation index (wetlands), acidity (forests), forest class (forest) and tree species (forest). Eventually, using the following two indicators gave the most balanced result in terms of statistical analysis and coverage of the EU27 countries.

- **Agro-ecological zones** were used as a proxy for the climate zones (GAEZ map v4 from FAOSTAT[1]) so as to differentiate between **forests** of similar types.
- **Eco-regions** set out by the EEA[2] were used to differentiate between **wetlands** of similar types.

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[1] *https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/7a10de20-7845-453d-8af9-90688ef5b0f9*

[2] *https://www.eea.europa.eu/data-and-maps/figures/dmeer-digital-map-of-european-ecological-regions*

Forests

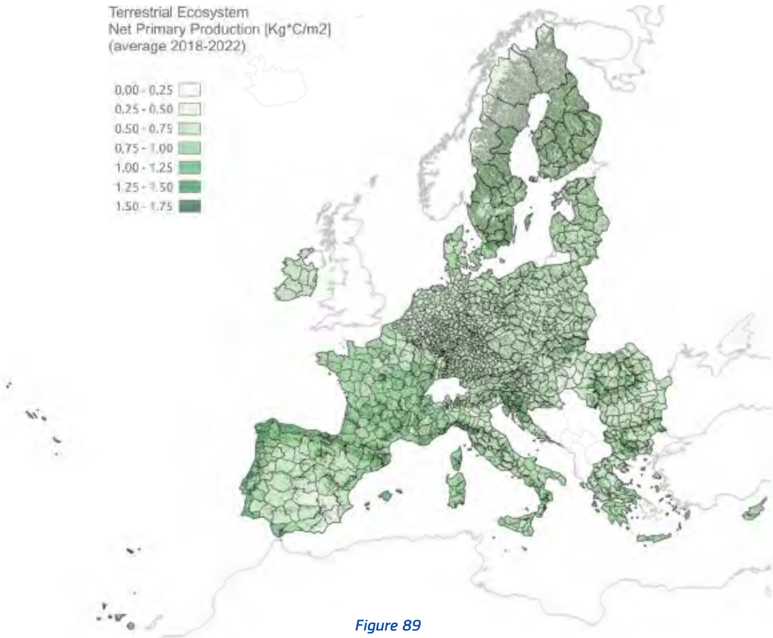

Figure 89

Net primary production of forest per surface units at NUTS-3 level .

Figure 90

Distribution of forest in the EU (source: Corine Land Cover, "forest" classes)

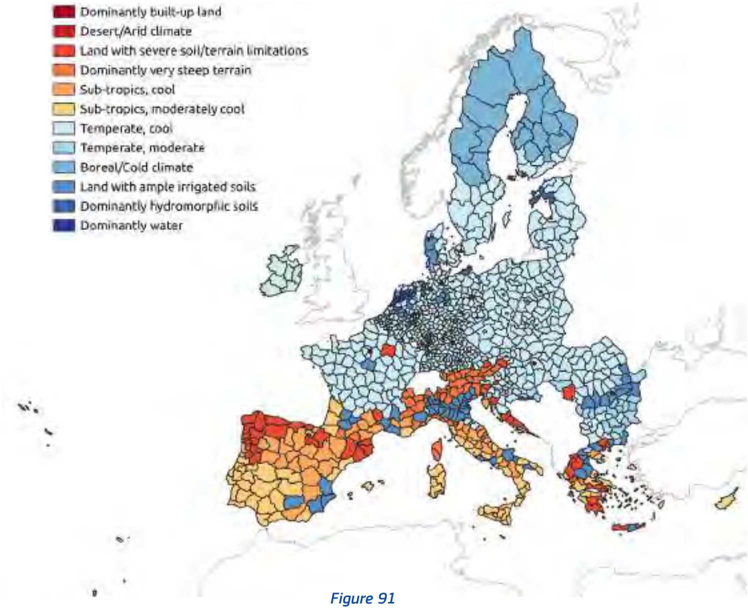

Figure 91

Vulnerability clusters used in the analysis for forests, based on agro-ecological zones.

Wetlands

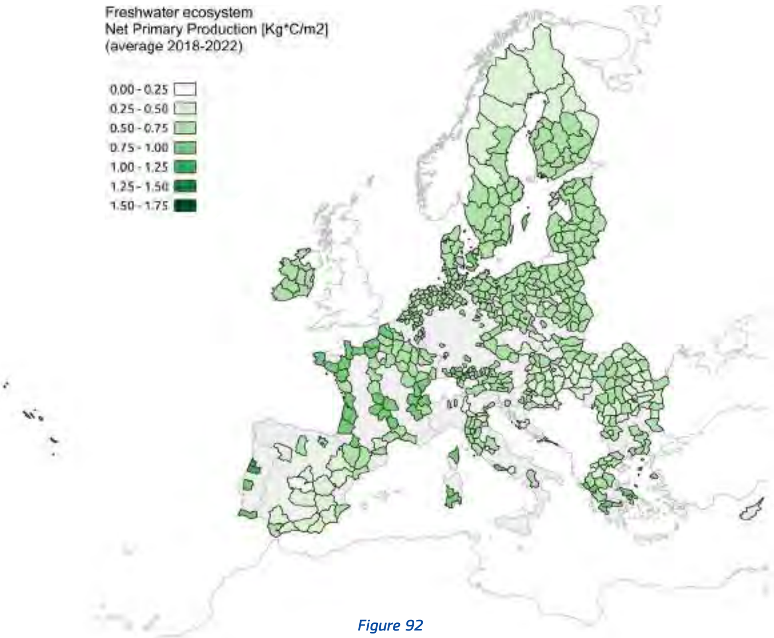

Figure 92

Net primary production of wetlands per surface unit at NUTS-3 level.

Figure 93

Distribution of wetlands in the EU (source: Corine Land Cover, "inland wetland" classes)

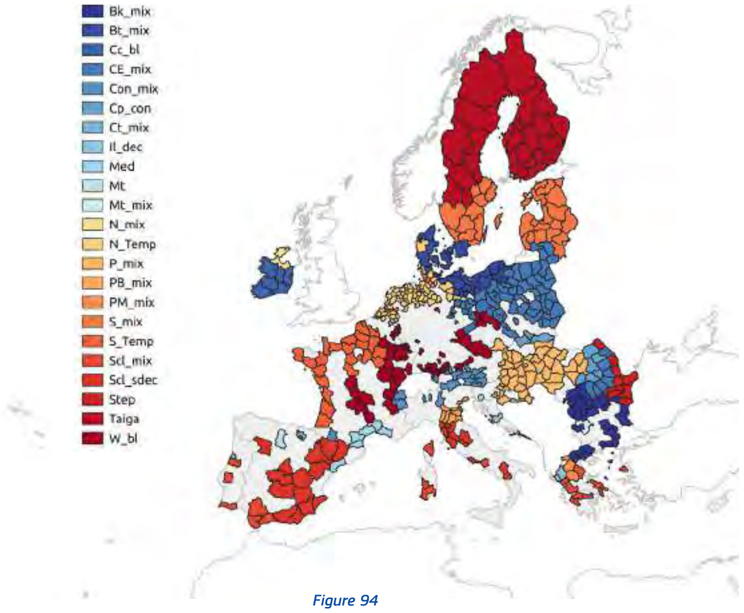

Figure 94

Vulnerability clusters used in the analysis for wetlands, based on the ecoregions

(Bk_mix = Balkan mixed forests; Bt_mix = Baltic mixed forests; Cc_bl = Celtic broadleaf forests; CE_mix = Central European mixed forests; Con_mix = Alps conifer and mixed forests / Pyrenees conifer and mixed forests; Cp_con = Carpathian montane coniferous forests; Ct_mix = Cantabrian mixed forests; Il_dec = Illyrian deciduous forests; Med = Northeastern Spain & Southern France Mediterranean / Crete Mediterranean forests; Mt = Northwest Iberian montane forests; Mt_mix = Rodope montane mixed forests/Dinaric Mountains mixed forests; N_mix = North Atlantic moist mixed forests; N_Temp = Northen Temperate Atlantic; P_mix = Pannonian mixed forests; PB_mix = Po Basin mixed forests; PM_mix = Pindus Mountains mixed forests; S_mix = Sarmatic mixed forests; S_Temp = Southern Temperate Atlantic; Scl_mix = Aegean & West Turkey sclerophyllous and mixed forest / Southwest Iberian Mediterranean sclerophyllous and mixed forests / Tyrrhenian-Adriatic sclerophyllous and mixed forests; Scl_sdec = Iberian sclerophyllous and semi-deciduous forests / Italian sclerophyllous and semi-deciduous forests; Step = East European forest steppe / Pontic steppe; Taiga = Scandinavian and Russian taiga; W_bl = Western European broadleaf forests).

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