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MODFABE
adapting by learning

Horizon 2020 - Research and Innovation Framework Programme
H2020-MSCA-IF-2018

MODFaBe – Modelling individual farmers behaviours in Coupled Human Natural Systems under changing climate and society
Project no. 832464

Report on climate change constraints affecting the Muzza system

Deliverable 2.1 (D2.1)

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Authors	Sandra Ricart, Andrea Castelletti
Content of this report	This report provides a revision of the literature regarding climate change stressors especially focusing on Italy and regional level when possible (northern Italy and Po Valley). The report includes: (i) identification of main climate change patterns and impacts, with a special focus on temperature and precipitation values, (ii) a selection of main climate change risks according to identified impacts, and (iii) the visualization of main climate change effects on agriculture.
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Abbreviations

ABM: Agent Based Models
C3S: Copernicus Climate Change Service
CHNS: Coupled Human-Natural Systems
EDO: European Drought Observatory
GDP: Gross Domestic Product
GMST: Global Mean Surface Temperature
IPCC: Intergovernmental Panel on Climate Change
NAO: North Atlantic Oscillation
PNACC: Piano Nazionale di Adattamento ai Cambiamenti Climatici
RCPs: Representative Concentration Pathways
SMI: Soil Moisture Index
SNAC: Strategia Nazionale di Adattamento ai Cambiamenti Climatici
SPI: Standardized Precipitation Index
SRES: Special Report on Emission Scenarios
SREX: Special Report on Extreme Events
WEF: Water-Energy-Food Nexus
WP: Work Package

1. Introduction

This Deliverable (D2.1) "Report on climate change constraints affecting the Muzza system" is part of Work Package 2 (WP2) "Climate change constraints affecting the Muzza system". The main objective of this work package is to provide a synthesis of the main climate change impacts and risks affecting agricultural activity in the Muzza system, in the Lombardy region (Italy), by addressing the gap between water scarcity and water demand scenarios. To this purpose, D2.1 aims to provide a review of the literature on climate change stressors, especially focusing on Italy and the regional level (northern Italy and Po Valley), including main impacts and risks. The report (because of Tasks 2.1, 2.2, and 2.3) sets a reference for WP4 ("Key behavioural rules from individual farmer' perception and key stakeholders' decision") and associated tasks 4.1 and 4.2 which will focus on data collection about climate change perception from farmers and managers through semi-structured interviews and survey. Besides, D2.1 will also set the baseline for WP5 ("Behavioural models of individual farmers and key stakeholders using artificial intelligence and machine learning technique") by integrating those key points (outputs) from the literature as new utility functions and multiobjective problems in the DistriLake model.

This deliverable reports an assessment of main climate change constraints affecting the Muzza system by considering both meteorological (e.g., historical trends, future scenarios) and socio-economic (e.g., impacts and risks, perception) issues. As a state-of-the-art report, it should be used or consulted by utility managers and operators, local government officials and planners, public interest groups, and end-users, like farmers. Starting with an overview of the project (Section 2), the report is structured in three parts:

- Part I: identification of main climate change patterns and impacts, with a special focus on temperature, precipitation, and soil moisture values (Section 3),
- Part II: a selection of main climate change risks according to identified impacts (Section 4), and
- Part III: visualization of main climate change effects on agriculture (Section 5).

Sections have been built upon the reviewed literature and additional sources such as databases, reports from public and private institutions, outputs from research projects. Key concepts and a set of key indicators have been considered from the review of the literature to provide a brief overview of the current situation of climate change constraints affecting the Muzza system.

2. MODFABE project overview

Worldwide water consumption continues to grow, and it is estimated that by the year 2030, more than 160% of the total water volume worldwide will be needed to satisfy global water requirements (Azhoni *et al.* 2018). Moreover, with available water resources diminishing in quantity and quality and increases in the range of water uses in competing sectors, water scarcity has become a critical issue (Fitton *et al.* 2019). Agriculture is the sector most affected by water scarcity as it accounts for 70% of global freshwater withdrawals and more than 90% of the consumption (including non- conventional water resources) (Ricart & Rico 2019). Consequently, irrigation systems are under pressure to produce more food with lower supplies of water (Levidow *et al.* 2014).

Climate change impacts such as high temperature, reduced rainfall, and increased frequency of extreme weather events will add new threats to irrigation systems and will compound existing human pressures through changes to hydrological processes and socio-ecosystem interactions (Reid *et al.* 2019). The mismatch between water supply and water demand in different temporal and geographical scales and according to different climate change scenarios calls for new approaches (Chen *et al.* 2018). Decision-makers need information on how climate change impacts affect water resources for all sectors, particularly agriculture, especially in the most drought-prone, water scarcity or surplus, and water competing users (Hunink *et al*. 2019).

Climate change and water resources management represent two necessarily interdisciplinary topics, in which the natural and social sciences must be integrated (Escribano-Francés *et al*. 2017). In the last decades, the shift to address the integrated management of water resources from a technocratic ''top-down'' to a more integrated ''bottom-up'' and participatory approach was motivated by the awareness that water challenges are complex, requiring integrated solutions and a socially legitimated planning process (Fritsch & Benson 2019). That is, assuming water flows as physical, social, political, and symbolic matters, it is necessary to entwining these domains in specific configurations in which water users, managers, and decision-makers could be directly involved (Ricart 2020).

Social learning is considered an important issue in achieving this goal of improving water management and decision-making processes (Johannessen *et al.* 2019). It refers to processes that involve active deliberation and engagement by end-users, managers, and key stakeholders with confronted water demands, which can lead to a new understanding or shared meaning to (1) increase adaptive capacity, (2) build trust and collaborative problem solving, and (3) ensure better co-working between stakeholders, who differently understand features of socio-environmental issues in climate change scenarios (Eriksson *et al.* 2019). The social perception of climate change is fundamental for two important reasons: first, because it constitutes a key component of the socio-political context within which policy-makers exercise their decisions in socio-ecological systems. The second reason is more direct: the process of mitigation and adaptation to climate change requires behaviour transformation and attitude change from those who each day make individual and participate in collective choices that have a huge impact on the planet climate balance (Antronico *et al.* 2020).

Water supply and demand nexus was generally overlooked in the modelling literature by mostly focusing on understanding the natural processes only while assuming one or a few scenarios of human actions generally treated as fixed boundary conditions (Giuliani *et al.* 2016). However, this unilateral perspective might no longer be appropriate if social-learning must be achieved, and a paradigm shift is required to put humans in the modelling loop (Wada *et al.* 2017). Modelling techniques have been recognized, also in social sciences, as effective computational techniques to simulate social influence processes in CHNS from interactions within a community of individual agents (van Bruggen *et al.* 2019). Consequently, modelling human behaviour can be used as a safe laboratory for policy experimentation, testing the effectiveness of strategies and policy measures on climate change by learning from human experience. Furthermore, modelling frameworks must find ways to glue the anthropogenic sphere with the hydrological systems such that the feedback between human activities and hydrological cycles can be addressed internally. Agent-Based Models (ABM) can accomplish this task by considering each agent as an active decision-maker who lives in the common environment and interacts within (Kremmydas *et al.* 2018). By modelling agents individually, the full effect of attribute and behaviour diversity of agents, which together give rise to the behaviour of a system, can be observed. The application of an ABM ensures not only the feedback between social (farmers' agents) and physical (water resources) environments but also the social network based on agents' interactions.

How farmers perceive climate change uncertainties, potential impacts, and risks is important because (Gardezi & Arbuckle 2020): 1) Local experience can be shared and compared and this would be useful to identify common patterns and individual strategies (to be transferred to policy-makers), and 2) assess the perception and effectiveness of climate change responses is the first step towards adaptation. Farmers are key constituents in the social-learning process of understanding both climate change impacts on food and water systems and how best to mitigate and adapt to these impacts (Soubry *et al.* 2020). Farmers develop their activity supporting the complexity of interrelated nature and human systems characterized by political, economic, institutional, cultural, and biophysical conditions (Abid *et al.* 2016). Accordingly, personal experience, local knowledge, and social-learning exchange between farmers and managers may help to promote mutual understanding and to reduce agricultural systems vulnerability. Besides, this could override political barriers to action on climate change and promote an integrated response to a shared problem (Marquart-Pyatt *et al.* 2014): How to ensure food and water security while addressing climate change impacts and risk management in a CHNS?

Modelling human behaviour, however, is rather a non-trivial task: human behaviour is well recognized as a complex non-linear, multi-variate process due to the high heterogeneity and uncertainties in human cognition and decision-making processes. The MODFABE project aims to increase the robustness of decision-making processes in CHNS by modelling farmers' perception and adaptation capacity to climate change. Departing from an existing very basic behavioural model (DistriLake) applied to the management of water supply and demand in the Lake Como to balance shoreline floods and irrigation deficit downstream (Li 2016), the MODFABE project aims to integrate observational data (farmers' perception) into the simulation model to increase the rationality of farmers' interventions in the decision-making processes considering multiple competing purposes and a multiobjective context. The updated behaviour model will contribute to characterize the water supply and demand side of the Muzza system – and its irrigation district as a case study– as one of the largest agricultural areas in northern Italy. MODFABE will offer "what-if" decision support functions to investigate new utility functions, optimization problems, and risk reduction options in the demonstration case study. This local context is a test to the understanding of the driving-factors affecting farmers' perception regarding climate change impacts and how their adaptation capacity affects the management of the CHNS. Results could be used to reformulate policy recommendations to better respond to climate change by considering the preferences shift toward a new equilibrium in decision-making processes to reduce the frequency of unsatisfactory system states (Mason *et al.* 2018).

A twofold question in today's climate change adaptation research will be addressed:

- Could behaviour modelling help farmers to promote actions and anticipate decisions to better adapt to climate change and become less vulnerable?

- Could social-learning from farmers' climate change adaptation capacity provide new social scenarios able to increase model robustness when addressing decision-making processes?

Both questions endeavour to connect climate change adaptation, a macro-level issue, with the behaviour and social learning from farmers and key stakeholders, a micro-level issue. The project also considers a systemic (water resources supply and demand) and stakeholder-centred (farmers, managers, and decision-makers) approach and seeks to collaboratively frame the issue of climate change by co-producing solution-oriented knowledge at the local scale from farmers' feedback. Results could be used to inform managers and decision-makers about the effectiveness of different types of interventions and to reformulate policies to better respond to climate change by considering the preferences shift toward a new equilibrium in decision-making processes to reduce the frequency of unsatisfactory system states (Mason *et al.* 2018). Furthermore, MODFABE will contribute to strengthening the role of farmers' perception of climate change impacts, actions, and barriers when planning interventions by highlighting the nexus between climate services and modelling. Consequently, managers and decision-makers will be empowered to perform climate perception proofs and adaptive policies to increase the robustness of the management of CHNS.

3. Climate change patterns and impacts

Key messages

- ✓ Since the 1980s, each successive decade has been warmer than any proceeding one since 1850.
- ✓ In general, a decrease in annual precipitation values is expected, but heavy precipitation has become more common since 1950 in terms of amount, intensity and frequency.
- ✓ Strong decrease in the SMI is simulated in the second half of the 21st century, also for the Alpine region

Climate change is altering the human relationship with the environment, modifying relatively stable climate factors, and making them uncertain, unpredictable, and threatening (Findlater *et al.* 2018). The climate is changing across the globe, causing several impacts and increasing the vulnerability of regions, economic sectors, and communities (Trenberth *et al.* 2011). The impacts of climate change vary across Europe, but nearly all parts of the continent are likely to feel its effects. As a complex process, climate change is acting as a selective force including a pronounced rise in air temperatures, a higher frequency and severity of extreme weather events (e.g., droughts, heat waves, heating days), together with higher temporal and spatial variability in precipitation (e.g., storms, flood risk, heavy rainfall) (IPCC 2014, OECD 2016).

Vulnerable regions include the Mediterranean basin and mountain areas, in which temperature rises larger than the European average and a decrease in annual precipitation and glacier extent and volume has been identified, respectively. The Mediterranean area is one of the most sensitive regions worldwide due to its population density, the concentration of economic activities in coastal zones, and its climatic borderline equilibrium. According to the *First Mediterranean Assessment Report* (MedECC 2020), the Mediterranean is at risk of suffering from levels and rates of climate and environmental changes now and in the foreseeable future that exceed global mean values.

The integrated analysis of climate scenarios for Italy shows that climate change is a determining element for risk factors, enabling new risks to emerge and/or amplifying pre-existing ones in an already critical context, directly affecting many socio-economic sectors such as agriculture (Spano *et al.* 2020). The *Piano Nazionale di Adattamento ai Cambiamenti Climatici* (PNACC) provides an overview of the main climate risk factors according to different regional climate zones by the period of reference (1981-2010). Six climatic regions or clusters, of which half are partially located in the north of the country, were identified and characterized according to the main climate indicators (Figure 1).

	Temperatura media annuale – Tmean (°C)	Giorni con precipitazioni intense – R20 (giorni/anno)	Frost days – FD (giorni/anno)	Summer days – SU95p (giorni/anno)
Macroregione 1 – Prealpi e Appennino settentrionale	13 (±0.6)	10 (±2)	51 (±13)	34 (±12)
Macroregione 2 – Pianura Padana, alto versante adriatico e aree costiere dell'Italia centro-meridionale	14.6 (±0.7)	4 (±1)	25 (±9)	50 (±13)
Macroregione 4 – Area alpine	5.7 (±0.6)	10 (±3)	152 (±9)	1 (±1)

	Precipitazioni invernali cumulate –WP (mm)	Precipitazioni cumulate estive – SP (mm)	95° percentile precipitazioni – R95p (mm)	Consecutive dry days – CDD (giorni)
Macroregione 1 – Prealpi e Appennino settentrionale	187 (±61)	168 (±47)	28	33 (±6)
Macroregione 2 – Pianura Padana, alto versante adriatico e aree costiere dell'Italia centro-meridionale	148 (±55)	85 (±30)	20	40 (±8)
Macroregione 4 – Area alpine	143 (±47)	286 (±56)	25	32 (±8)

Figure 1. *Average values and standard deviation of main climate indicators for each macro-region identified for northern Italy.*

The projected changes for COSMO RCP4.5 2021-2050 vs. 1981-2010 have been characterized for each of the three zones affecting northern Italy (Figure 2). *Cluster 1* (dry-warm winter) is characterized by a general reduction in precipitation and a significant reduction in frost days (by 20 days/year) and in snow cover (by 21 days/year). *Cluster 2* (hot-dry summer) is described by a significant increase in summer days (by 18 days/year) and by a reduction in winter and, above all, summer rainfall (average value of the reduction equal to 27%). This cluster also shows a significant reduction in frost days, snow cover, and evaporation. Finally, *cluster 3* (rainy winter-dry summer) is affected by an increase in winter rainfall (average value about 8%) and a significant reduction in summer ones (average value about 25%). Likewise, there is a significant increase in both extreme precipitation phenomena (R95p) and summer days (14 days/year).

	Tmean (°C)	R20 (giorni/anno)	FD (giorni/anno)	SU95p (giorni/anno)	WP (%)	SP (%)	SC (giorni/anno)	Evap (%)	R95p (%)
	1.2	-2	-20	1	-8	-15	-21	1	-1
	1.4	-1	-20	18	-4	-27	-12	-6	1
	1.2	1	-9	14	8	-25	-1	-2	11

Figure 2. *Map and anomalies average values of identified clusters (COSMO RCP4.5 2021-2050 vs 1981-2010). Source: Adapted from PNACC (2018).*

Considering temperature and precipitation patterns as the main issues to deepen on climate change impacts, the next sections will be focused on both variables, in addition to soil moisture as the result of their behaviour.

3.1. Temperature

Global Mean Surface Temperature (GMST) is increasing at the rate of 0.2±0.1°C per decade, reaching 1.1±0.1°C above the pre-industrial period (1850–1900) in 2019 (Hoegh-Gulberg *et al.* 2019). According to Berkeley Earth, a non-profit research organization providing independent analyses of global mean temperature changes since 2013, the global mean temperature in 2020 is estimated to have been 1.27°C above the average temperature of the late 19th century (Figure 3). This is ≈0.02ºC cooler than in 2016, and ≈0.02ºC warmer than 2019. As a result, 2020 was nominally the second warmest year to have been directly observed, though the three warmest years are all tightly clustered together relative to the uncertainty in these measurements. Moreover, the last six years stand out as a period of significant warmth well above all previous years since 1850. In addition to long-term warming, individual years are also affected by interannual variations in weather. For example, 2016 was warmed by an extreme El Niño event with exceptional characteristics that peaked in November and December of 2015. By contrast, 2020 began with neutral conditions and finished with a moderate La Niña extreme that is likely to have a larger impact on 2021.

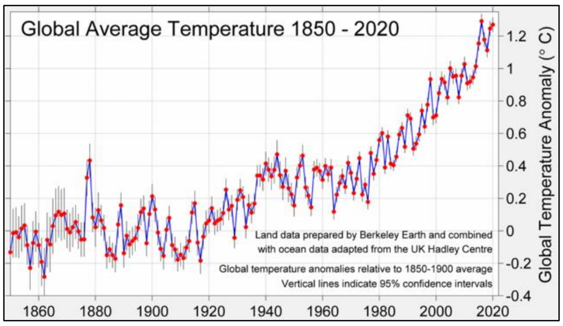


Figure 3. *Map and anomalies average values of identified clusters (COSMO RCP4.5 2021-2050 vs 1981-2010). Source: Berkeley Earth and Copernicus Climate Change Service (C3S).*

Additionally, the ten warmest years on record have all occurred since 1998, and 9 of the 10 have occurred since 2005, while 1998 is the only year from the 20th century still among the ten warmest years on record. Globally and looking back to the late eighties, a pattern emerges: except for 2011, as each new year is added to the historical record, it becomes one of the top 10 warmest on record at that time, but it is ultimately replaced as the "top ten" window shifts forward in time, and the IPCC SR15 report concludes that since the 1980s, each successive decade has been warmer than any preceding one since 1850.

A recent study by Cardell *et al.* (2020) deepens on future summer trends to show that maximum temperatures will exceed the present T_{max}95 more than 10% of days throughout the domain by the late 21st century and especially affecting the regions of the South-Eastern Europe and the Mediterranean. Average annual mean temperatures in the Mediterranean Basin have risen by 1.5ºC since pre-industrial times (1861-1890), approx. 0.4ºC above the global average (MedECC 2020). A study carried out by Kjellström *et al.* (2018) shows that Europe will warm in all seasons in the future and the simulated temperature changes in Europe are mostly larger than the global mean warming.

The ensemble median drought area for the end of the 21st century is estimated to be about 16%-18% of the European territory, and the duration is approximately 9 to 12 months for all of the considered warming levels (Samaniego *et al.* 2018). The increased occurrence of drought and water scarcity is predicted in many regions (Koutroulis *et al.* 2018) but previous studies have demonstrated that drought episodes typically for southern European countries are expanding to Eastern and Western Europe (Spinoni *et al.* 2015). Furthermore, this tendency is most pronounced in summer where warming is strongest (which corresponds to a warming increase of almost +2ºC or +2.5ºC compared to pre-industrial conditions).

Arnell *et al.* (2019) calculated 30 impact indicators at the regional and global scales (Figure 4) using spatially explicit impacts models and climate scenarios representing different levels of increase in global mean temperature (1.5ºC, 2.0ºC, and 4.0ºC) above pre-industrial levels constructed by pattern-scaling. The study highlights how at the global scale, all the impacts that could plausibly be either adverse or beneficial are adverse, and the impacts of floods, droughts, and heat waves increase with global mean temperature.

However, uncertainty varies between regions, with Europe as the region with a higher increase in temperature, heat wave frequency, and runoff increase, while river flood frequency reduces short term.

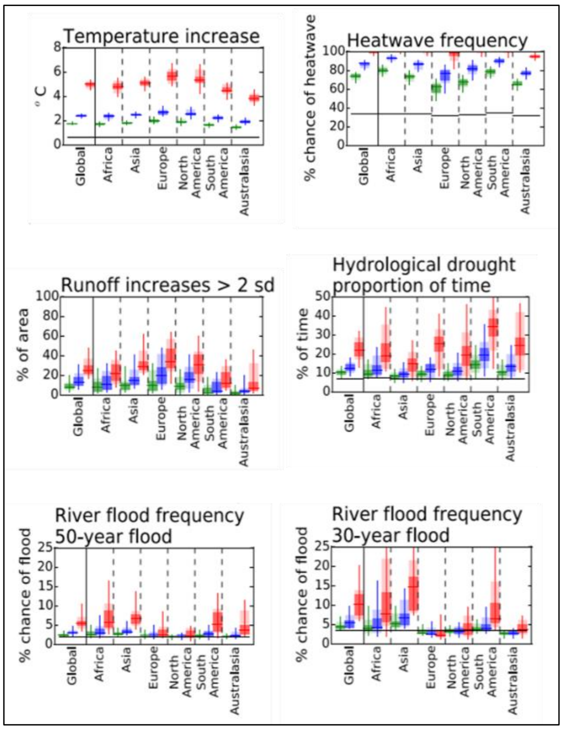


Figure 4. *Impacts at 1.5ºC, 2ºC, and 4ºC above pre-industrial levels. Note: The horizontal black lines show impacts with the 1981–2010 climate. The horizontal coloured lines (green=1.5ºC, blue=2ºC, and red=4ºC) show the median impact, the dark shading shows the interquartile range and the light shading shows the 10th to 90th percentile range. The vertical lines show the range between lowest and highest impact. Legend: Temperature increase: Regional average increase in temperature. Averaged over cells with more than 1000 people in 2010. Heatwave frequency: Likelihood (%) that a year will contain a heat wave, with a maximum temperature greater than the 98th percentile of the warm season temperatures for at least two days. Averaged over cells with more than 1000 people in 2010. Runoff increases > 2 Sd: % of region with a decrease/increase in average annual runoff more than twice the standard deviation of 30-year average runoff. Hydrological drought proportion of time: Proportion of time spent in hydrological drought (Standardised Runoff Index). Averaged over cells with more than 1000 people in 2010. River flood frequency 50-year flood: Likelihood (%) that a year will contain a flood greater than the reference period 50-year flood (2% likelihood). Averaged over cells with more than 1000 people in 2010. River flood frequency 30-year flood: Likelihood (%) that a year will contain a flood greater than the reference period 30-year flood (3.33% likelihood). Weighted by cropland area.*

For Italy, 2020 is also the second warmest year since the start of the observations (Figure 5) (+1.56ºC compared to the period 1961-1990), after the records already recorded in 2018 and 2019 (Spano *et al.* 2020). Furthermore, eight of the ten years warmest in the time series were recorded from 2011 onwards, with anomalies between +1.26ºC and +1.71ºC.

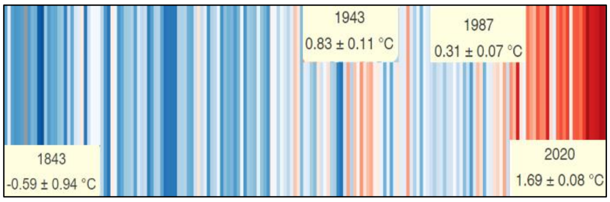


Figure 5. *Italy climate stripe. Source: Berkeley Earth.*

According to the Berkeley Earth database, 71 of the 120 top-ten maximum monthly records since the 19th century occurred during the 21st century, and 38 of them in the last decade (2011-2020), while annual records have been concentrated in the past seven years consecutively (2014-2020). Furthermore, and considering seasonal changes (Figure 6), every month has at least one maximum record in the 21st century, being the years with the warmest records: 2018 and 2019 (7 months), followed by 2012, 2014, and 2015 (6 months), and 2003 and 2017 (5 months). The warmest month's concentration is between February-April, June-August, and October, being August the month with the highest number of records.

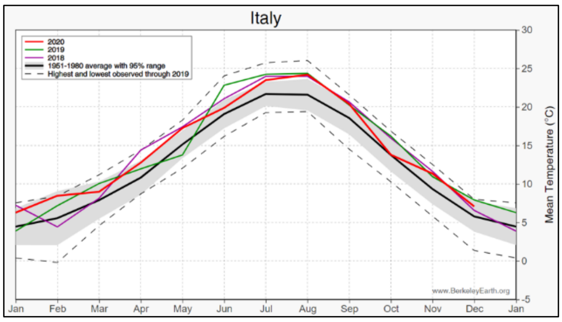


Figure 6. *Mean temperatures according to seasonal changes: 2018-2020 vs reference period (1961-1980). Source: Berkeley Earth.*

This tendency is similar at the local scale and for locations nearby to the Muzza system, such as Milan, in which 2020 presents 5 of 12 months into the top-ten maximum monthly records (January, February, April, August, and

November). On the contrary, historical records considering the coldest annual and monthly averages have not been surpassed in the 21st century, and only 23 of the 130 records occurred in the second half of the 20th century (1950-1999).

Looking at the future, EURO-CORDEX modelling of the geographic distribution of temperatures by 2021-2050 agrees to simulate an increase in temperature compared to the reference period (1981-2010) mainly uniformly distributed throughout Italy (Figure 7), although some differences are appreciable especially in summer.

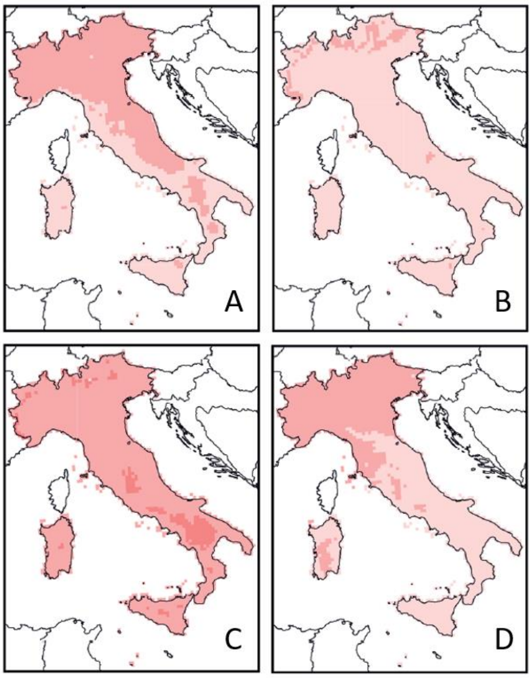


Figure 7. *Temperature variation at 2m on a seasonal scale over Italy by the EURO-CORDEX ensemble according to the RCP4.5 scenario for the period 2021-2050 compared to the reference period 1981-2010. Legend: A=winter (DJF), B=spring (MAM), C=summer (JJA), D=autumn (SON). Source: Spano et al. (2020).*

Likewise, previous investigations focused on the Alpine region highlighted a temperature increase in all seasons with the largest values for summer season by the end of the 21st century (Coppola *et al.* 2018). According to Smiatek *et al.* 2016 simulated changes calculations for 2071–2100 related to the 1971–2000 period in the Alps (Figure 8), the temperature will increase in the seasonal mean 2m temperature of 2.5ºC in fall and winter, 2.4ºC in summer, and 1.9ºC in spring (Figure 9).

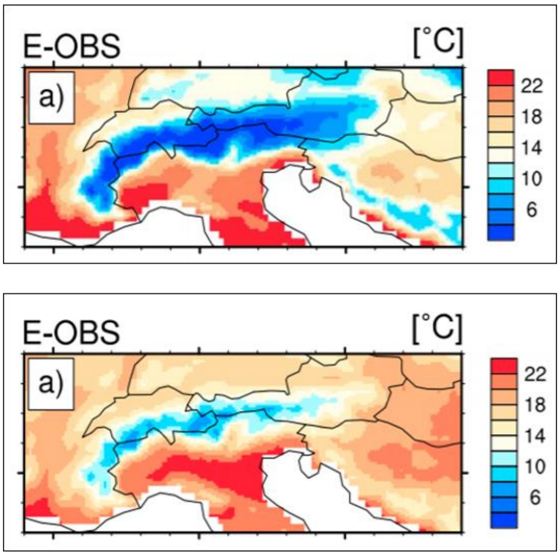
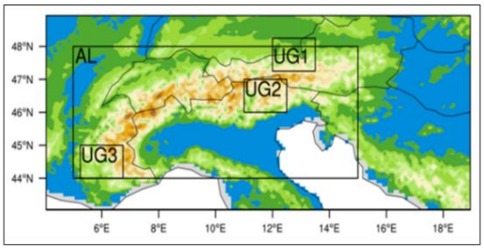


Figure 8. *Observed mean seasonal temperature for the winter season (top) and summer (down) for 1971–2000 period. Source: Smiatek et al. (2016).*



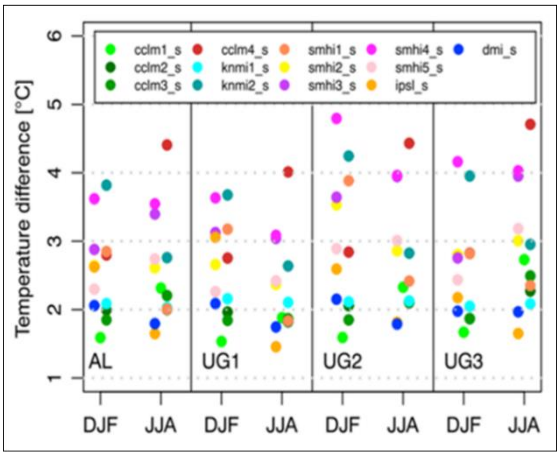


Figure 9. *Changes in the area mean winter (DJF) and summer (JJA) temperature as difference 2071–2100 to 1971–2000 in the investigation areas AL, UG1, UG2, and UG3. Source: Smiatek et al. (2016).*

Running up to 13 dynamic regional downscaling experiments with the CMIP5 (Coupled Model Intercomparison Project Phase 5) and under the RCP4.5 scenario, the authors conclude how all simulations reveal a temperature increase in both winter and summer seasons, although single simulations differ up to 3.2°C for the projected future warming. In the same line, Bucchignani *et al.* (2016) projected a general temperature increase of about 3°C in all seasons and over the whole of Italy, including peaks of 4°C) over the Po Valley in winter and over the whole north-west area in summer (Figure 10). In this same line, the study carried out by Vezzoli *et al.* (2015) shows how the Po Valley is expected to warm more than the Alps (Figure 11), by identifying positive temperature anomalies range between 1.7°C (2.4°C) in spring and 3.1°C (3.7°C) in summer for RCP4.5(RCP8.5), and between 1.6°C (2.4°C) in winter and 2.7°C (3.1°C) in summer for RCP4.5-QM(RCP8.5-QM).

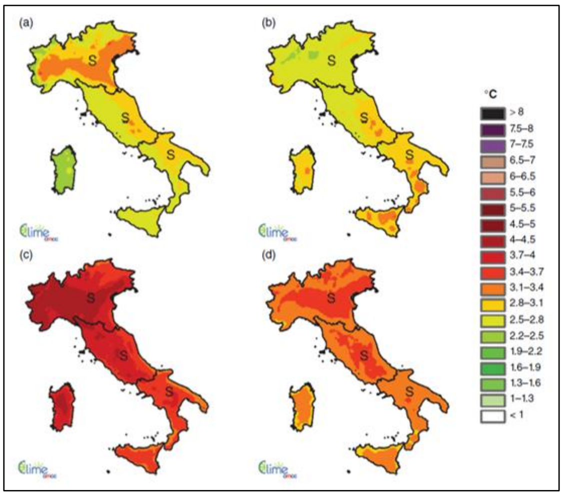


Figure 10. *Temperature climate projections, RCP4.5: seasonal differences (°C), between the average value over 2071–2100 and 1971–2000 for different seasons. Legend: (a) DJF, (b) MAM, (c) JJA and (d) SON, S=significant, NS=not significant.*

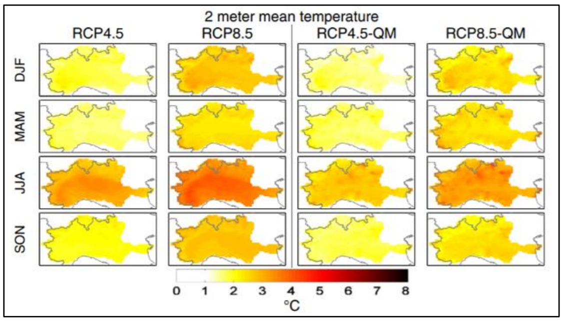


Figure 11. *Anomalies in 2m mean temperature (°C) over Po River basin, for the period 2041–2070. Note: Climate projections are obtained nesting the regional climate model COSMOCLM into the global climate model CMCC-CM. The bias in climate projections is corrected applying the distribution derived quantile mapping. The left side refers to raw CMCC-CM/COSMO-CLM outputs, right side to the bias-corrected climate. Source: Vezzoli et al. (2015).*

3.2. Precipitation

Precipitation increases globally, but at the regional level, relatively complex patterns of change can be observed, with areas of increased and areas of decreased precipitation. A decline in mean precipitation is projected for the Mediterranean area (Cramer *et al.* 2018), following a year-round decrease in opposition to the atmospheric moisture content. These patterns are closely related to changes in global circulation features, global energy and momentum budgets, local forces (e.g., topography, land use), and energy and water fluxes affecting convective activity (Thackeray *et al.* 2018). However, increases in heavy precipitation –rainfall amounts greater than 100mm (Q_{100}) recorded in less than a day and often within just a few hours that could lead to devastating flash flooding and floods– have also been documented in the Mediterranean during the fall season even when meaning total precipitation decreases. This can occur when the probability of precipitation (the number of events) decreases, or if the shape of the precipitation distribution changes (EEA 2017b). According to the IPCC AR5 report, heavy precipitation has become more common since 1950 in terms of amount, intensity, and frequency (Lehmann *et al.* 2015).

Although it is difficult to determine a meaningful trend in precipitation, especially since the 1950s, a general decrease in precipitation seems to be marked in the latter part of the 20th century over southern Europe, southward to the Mediterranean (Polade *et al.* 2017). According to the CS3, annual precipitation trends during the past 20th century were characterized essentially by enhanced precipitation in central Europe (i.e., north of the Alps), with increases ranging from 10% to close to 50% (Dore 2005). By contrast, the region stretching from the Mediterranean through central Europe (the Mediterranean Central

Area) has experienced decreases in precipitation by as much as 20% in some areas, but is the most exposed region in southern Europe to aggressive rainfall (Diodato *et al.* 2020). The interannual variability seems to have decreased in the latter part of the record: the amplitude of departures in precipitation from long-term averages are far less than in the first half of the past century (Figure 12).

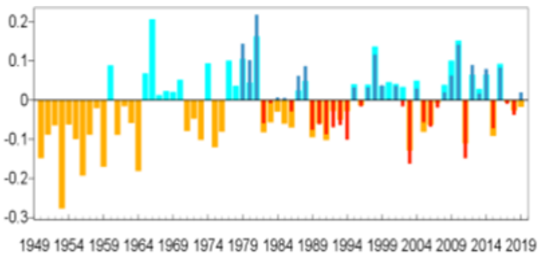


Figure 12. *European precipitation annual averages 1949-2019, relative to the 1981-2010 reference period. Note: ERA5 (blue/red), E-OBS (light blue/orange). Source: European State of the Climate 2019. Copernicus Climate Change Service.*

In general terms and according to the data provided by the CS3, northern Europe, and some parts of western and southern Europe, experienced a wetter-than-average year compared with the 1981-2010 reference period, including an above-average of precipitation in the Alps in 2019 (Figures 13 & 14). The wetter-than-normal conditions in these areas were mainly due to high levels of precipitation during the last three months of the year: Precipitation anomalies of up to 300mm above average (Q_{300}) were recorded during the period from October to December for regions bordering the northern Mediterranean coast, including northern Italy and the Alps. The impact of the large amounts of precipitation at the end of the year is also reflected in the river discharge patterns, for which high river discharge can lead to flooding, while low river discharge can, in extreme cases, result in drought and itself be a result of drought (EEA 2017a). During 2019, Europe saw below-average river discharge for two-thirds of the year. However, the discharge was generally within the reference period (1991-2016) range, while the transition from below-average to above-average conditions occurred between November and December.

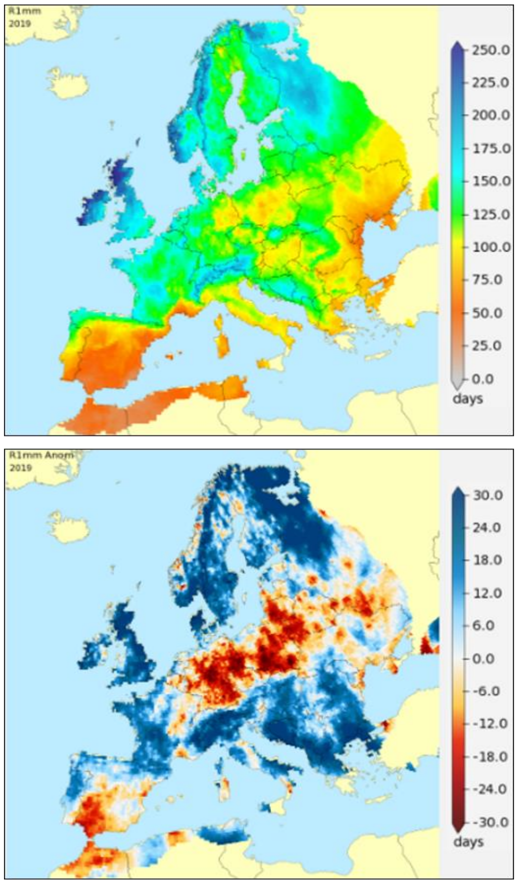


Figure 13. *Number of wet days in 2019 (left) and anomaly relative to the 1981-2010 reference period (right). Source: European State of the Climate 2019. Copernicus Climate Change Service.*

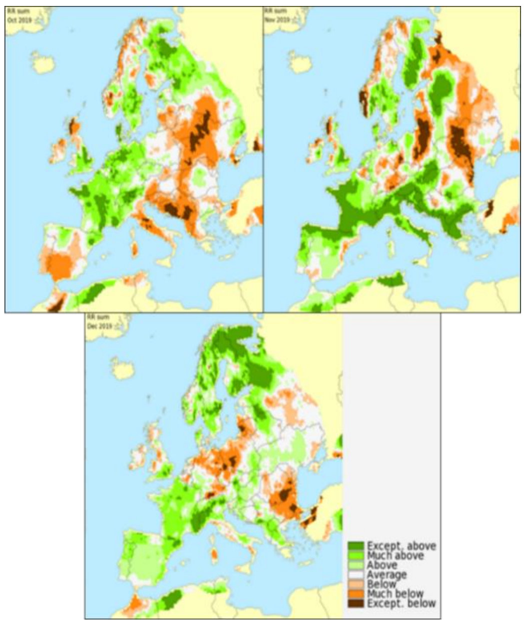


Figure 14. *Exceptional precipitation per month (RR sum) in Oct. (left), Nov. (middle) and Dec. (right) 2019. Note: The*

categories 'exceptionally above (below)', 'much above (below)', 'slightly above (below)' and 'average' relate to the percentile ranges >90 (<10), 75-90 (10-25), 60-75 (25-40) and 40-60 for the 1981-2010 reference period. Source: European State of the Climate 2019. Copernicus Climate Change Service.

Moreover, the annual median river discharge projected a decrease for the Mediterranean area in all four seasons. A north-south pattern emerges as regards low flows and groundwater. Declines in low flow up to 30% are projected under a 2ºC warming scenario for the Southern Europe region. The declines in low flow magnitudes may impact cooling water intake for industrial and energy production activities, irrigation water availability, critical environmental flow conditions, as well as hydropower potential. For example, with a 2ºC global warming, projections show a 4% decrease of hydropower annual inflow for south-west Europe, including northern Italy (Ciscar *et al.* 2018).

A recent study by Brogli *et al.* (2019) highlights how the Mediterranean drying pattern depends on the season by simulated global and regional circulation patterns for 30 years historical (1971-2000) and future (2070-2099) periods. In addition to the historical and future simulations, complementary experiments have been carried out by modifying the initial and boundary conditions according to thermodynamics, sea surface temperature, and mean state and circulation, plus the full climate change signal. By comparing summer and winter seasons and according to their results in precipitation changes, in both seasons, whenever the mean precipitation decreases, the decrease in precipitation is connected to decreasing precipitation frequency, while the precipitation intensity generally increases due to the increased moisture availability. During the summer period and in absolute numbers, the simulations project a precipitation decline of ≈30mm/season. Although the absolute numbers depend on the Mediterranean sub-region, a decreasing pattern from north-west to south-east has been identified (Figure 15). For Italy, full climate change pattern simulated by the end of the 21st century and focused in the summer shows a decrease in mean and frequency values about 30% although without sensitive changes in the intensity of the precipitation. On the contrary, the same drivers leading to a precipitation decline in summer do not generally induce decreasing precipitation in winter.

As reported by the *Strategia Nazionale di Adattamento ai Cambiamenti Climatici* (SNAC), the Alpine region is projected to a significant decrease in summer precipitation and the increase in winter precipitation (in the form of rain and not snow), together with the acceleration of the melting processes of the cryosphere, will cause significant changes in the mountain hydrological regime, consisting in a decrease in the summer run-off and above all in a considerable increase in winter run-off with consequences in terms of hydrogeological risk.

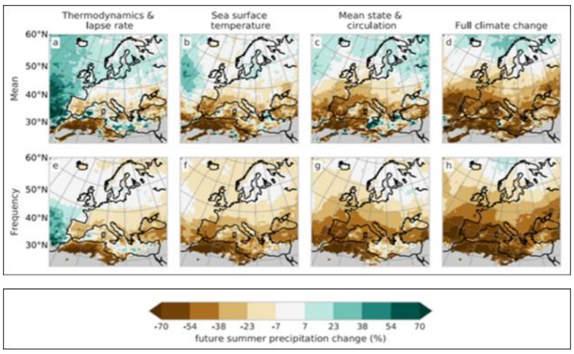


Figure 15. *Fractional summer precipitation changes: (a)–(d) mean, (e)–(h) frequency, and (i)–(l) intensity. Note: The columns show these changes from left to right for the four experiments TDLR, SSTE, MEA, and FCC. The changes are evaluated between 2070–2099 and 1971–2000 assuming the RCP8.5 emission scenario. Regions with a climatological rain amount of <0.9mm/season are masked and shown in grey.*

However, large parts of southern Europe are simulated to obtain less precipitation (although with larger uncertainty than in temperatures), while the regime of rainfall extremes events in some specific areas could be significant, as projected in Italy (Libertino *et al.* 2019). The study carried out by Rajczak & Schar (2017) identifies how the future character of precipitation will undergo significant changes. In the majority of seasons and regions and compared to present-day conditions, heavy precipitation events intensify, but changes in the overall character of precipitation are complex and depend on season and location. Extremes are subject to a general, and in many areas pronounced, intensification (Giorgi *et al.* 2019). For example, the most obvious, distinct, and widespread intensifications of heavy and extreme precipitation events by often more than +25% are found north of the Alps and in cold seasons. In summer, projections are associated with substantial uncertainty but exhibit an intensification of extreme rainfall events.

Likewise, precipitation change patterns indicate less precipitation in summer, particularly south of the Alps, but more precipitation in winter at the end of the 21st century (Gobiet *et al.* 2014). Moreover, the last report on climate change carried out by the Euro-Mediterranean Center on Climate Change (CMCC Foundation) highlights the greatest precipitation variations in winter according to the RCP4.5 scenario, with an increase of up to 9% in precipitation in the Alps and partially the Po Valley (Spano *et al.* 2020).

Besides, a higher than the normal number of wet days – defined as the number of days with precipitation amounts above 1mm – was observed in the Alps and some parts of Italy and the Adriatic coast, especially during the spring, with many areas seeing over 30 days more than average. On the contrary, summer was drier than average over large parts of southern Europe and the eastern Alps (EEA 2017a).

According to Bucchignani *et al.* (2016), annual precipitation time series (5-year running mean) and trend lines for northern Italy highlights a slight decrease for RCP4.5 and a more evident reduction for RCP8.5 (Figure 16). The general precipitation reduction, along with the increase in the winter season over northern Italy, agrees with projections described by previous works from Giorgi & Lionello (2008) and is due to circulation change patterns (increasing anticyclonic circulation) that will affect the whole Mediterranean region.

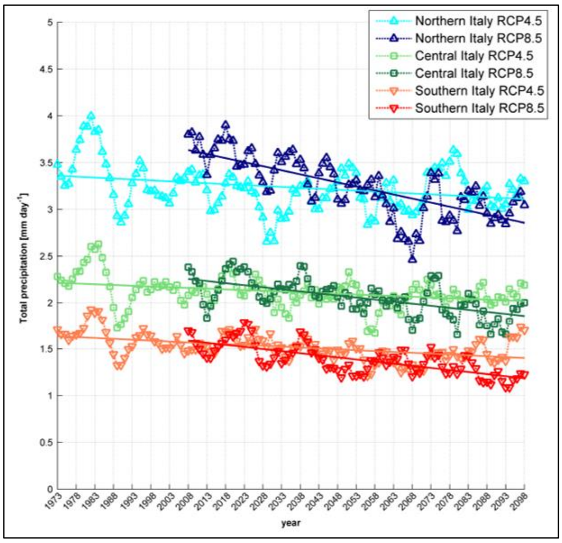


Figure 16. *Time series of precipitation and trend lines (mm day−1) over northern, central and southern Italy (5-year running mean) for the RCP4.5 and RCP8.5 scenarios. Source: Bucchignani et al. (2016).*

Likewise, most of the analyses on the effects of climate change focus on the largest and most important districts and river basins, including the Po River Basin. Precipitation distribution on this basin is more complex than temperature: the alpine basins of Oglio, Adda, and Ticino Rivers, effluents of the northern Italy lakes receive the maximum precipitation in summer and the minimum in winter, while precipitation in the remaining areas of the river basin is characterised by two maxima, in spring and autumn, and two minima, in summer and winter. Coppola *et al.* (2014) compared the medium-long term scenario (2020- 2050) with the historical data series (1960-1990) of the upper Po basin to show an anticipation of the spring rate peak from May to April, due to the accelerated melting of snow. The outflow is decreasing for the whole year except the winter period, while the variation of the winter runoff is concentrated in the northern part of the basin, increasing by 40% in the high-altitude areas, while the flat parts recorded an increase of 20%. In spring the outflow decreases by 20% along the entire course of the Po river and reaches 40% in the northern and southern extremities of the basin.

Although regional and local precipitation is much more variable from year to year than temperature, and this makes it much harder to predict future precipitation changes (Dai *et al.* 2018), low and high flow discharge have been projected for the Po Valley. According to Vezzoli *et al.* (2015), low flows are concentrated between July and September, and their duration is expected to increase. In the 2041–2070 period and according to RCP4.5-QM (RCP8.5-QM) simulation, low flow duration changes from 16 to 27 (28) days in July, from 17 to 27 (28) in August, and from 7 to 18 (16) in September (Figure 17).

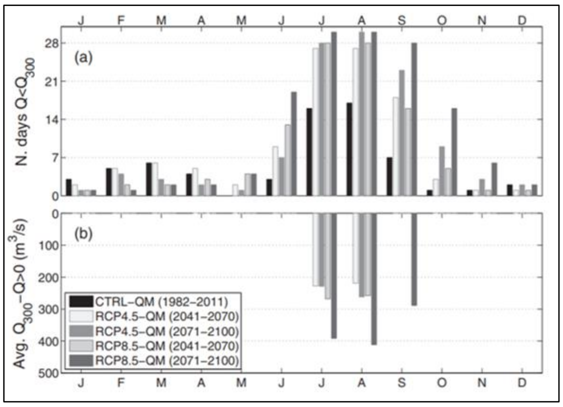


Figure 17. *Average number of days within each month with Q<Q300 for the CTRL-QM, RCP4.5-QM and RCP8.5-QM simulations (a), and average monthly deficit concerning Q300 threshold (b). Legend:* Q_{300}*=flow rate exceeding 300 days of duration. Note: Climate projections are obtained nesting the regional climate model COSMOCLM into the global climate model CMCC-CM. The bias in climate projections is corrected applying the distribution-derived quantile mapping. The left side refers to raw CMCC-CM/COSMO-CLM outputs, right side to the bias-corrected climate. Source: Vezzoli et al. (2015).*

On the opposite, high flows occur mostly in autumn and spring (flood seasons) and the volume associated with autumnal events is higher than the spring ones (Figure 18).

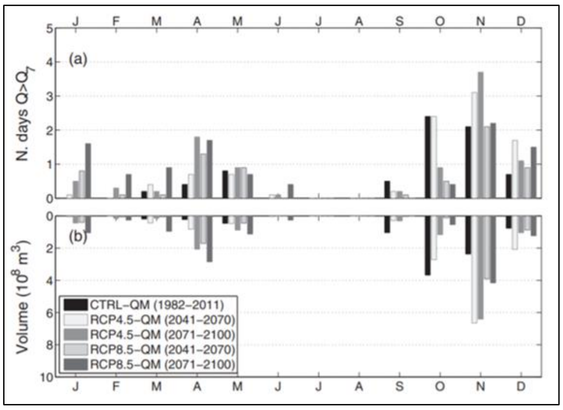


Figure 18. *Average number of days within each month with Q>Q7 for the CTRL-QM, RCP4.5-QM and RCP8.5-QM simulations (a), and average monthly deficit concerning Q7 threshold (b). Legend:* Q_7*=the discharge that is exceeded, on average, for 7 days a year or with an exceedance probability=0.02. Note: Climate projections are obtained nesting the regional climate model COSMOCLM into the global climate model CMCC-CM. The bias in climate projections is corrected applying the distribution-derived quantile mapping. The left side refers to raw CMCC-CM/COSMO-CLM outputs, right side to the bias-corrected climate. Source: Vezzoli et al. (2015).*

In the study by Vezzoli *et al.* (2015), for the two scenarios RCP4.5 and RCP8.5, it has been estimated that the average annual outflow of the main Po river shaft decreases for the periods 2041-2070 and 2071-2100, compared to the reference 1982-2011 (Figure 19). Moving from the medium to long term (2041-2070) the outflow decreases between May and November, while it remains constant during the rest of the year. In summer, the precipitation is about 1/3 less than in the control period under both scenarios either for raw and bias-corrected precipitations for RCP4.5(-QM) the reduction is almost constant across the season. In terms of spatial distribution, the Po Valley is characterised by the maximum anomalies while the Alps are characterised by lower changes. In autumn, RCP4.5(-QM) project more precipitation, on average 18% than the control period, in all months, especially on the eastern part of the basin and along the main river channel, instead, under RCP8.5(-QM) negligible variations 0.9% (-1.6%) are expected, with September and November anomalies that compensate each other.

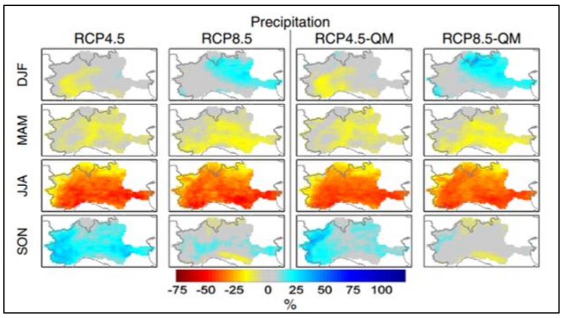


Figure 19. *Anomalies in seasonal precipitation in % and over Po River basin, for the period 2041–2070. Note: Climate projections are obtained nesting the regional climate model COSMOCLM into the global climate model CMCC-CM. The bias in climate projections is corrected applying the distribution-derived quantile mapping. The left side refers to raw CMCC-CM/COSMO-CLM outputs, right side to the bias-corrected climate. Source: Vezzoli et al. (2015).*

Moreover, Pedro-Monzonís *et al.* (2016) studied the water availability of the Po river in the RCP4.5 scenario: compared to current conditions, the volume of water reserves drops from 95 to 72 km^3, while it is also interesting to note how the increasing evapotranspiration contributes more significantly than anthropogenic withdrawals (three times as much in the RCP4.5 scenario).

3.3. Soil moisture

Soil moisture or the amount of water contained in the unsaturated soil layer is directly related to the temperature patterns as an integral and dynamic part of the hydrologic cycle and the precipitation. This water-storing layer is the result of non-linear interactions among different hydrometeorological and biophysical processes that control precipitation, evapotranspiration, and runoff (Ghannam *et al.* 2016). These interactions constitute soil moisture a regulatory agent of plant growth and nutrient uptake, affecting water, energy, and biochemical cycles, and even regulates natural hazard phenomena. Moreover, low soil moisture supply and high atmospheric water demand are considered as the two main drivers of dryness stress on vegetation, which can cause large threats to agricultural production (Liu *et al.* 2020). Recently, it has also been shown that the capacity of land ecosystems to act as a future carbon sink is highly dependent on the influence of soil moisture on ecosystem carbon fluxes (Green *et al.* 2019). Over the last decades, soil moisture in Europe presented a declining trend, being 2019 the year with the second-lowest level since at least 1979 (Figure 20). Significant decreases in summer soil moisture have been also identified by the European Environment Agency when modelling soil moisture content over the past 60 years in southern Europe. Results describe a significant reduction of the summer soil moisture up to 8 litres/m^3 in ten years in countries such as Spain, France, or Italy.

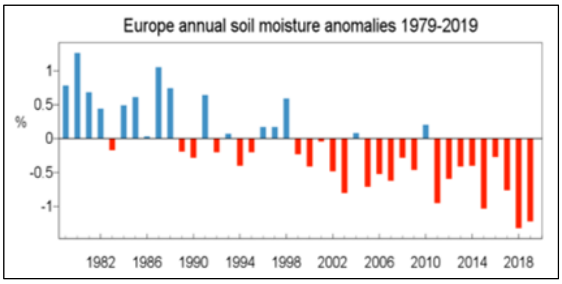


Figure 20. *Soil moisture anomaly annual averages 1979-2019, relative to the 1981-2010 reference period. Note:* The soil moisture represents the volumetric moisture content of the top 7 cm of soil. From an agronomic point of view, the first 7 cm provides are indicative of water availability for plants. Source: European State of the Climate 2019. Copernicus Climate Change Service.

Recent research on the Soil Moisture Index (SMI) and droughts frequency carried out by Grillakis (2019) confirms how severe SMI category seems to decrease for all European regions, expecting more frequent episodes than in the recent past, especially in the Mediterranean (Figure 21). Likewise, results show that unprecedented drought events in the historical period are expected to occur both short-term as well as to the end of the 21st century and for both scenarios (RCP2.6 and RCP6.0), regardless of the degree of mitigation that will be followed. These events are characterized by their unforeseen spatial extent and their duration, that can reach up to three years, but also the increased frequency of occurrence that can reach one or two events per decade.

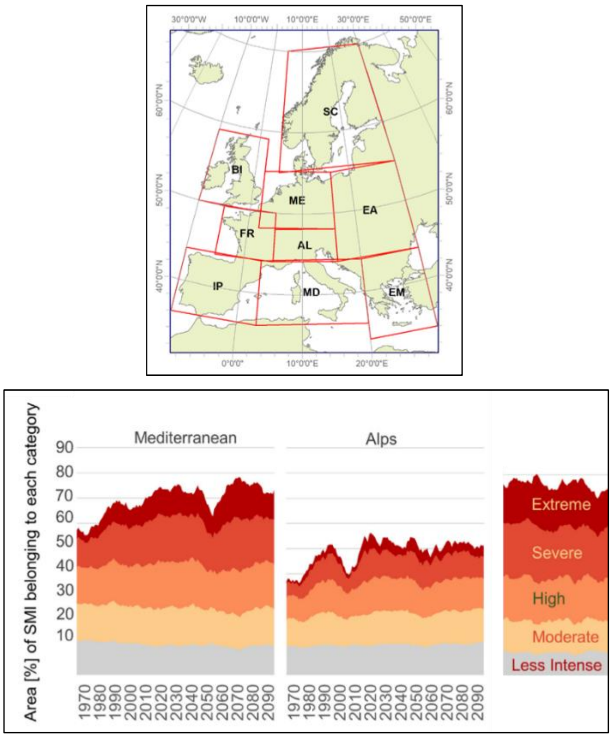


Figure 21. *Percent of area within each SMI category for two focus regions, under RCP2.6 scenario. Note: Legend on the left map: BI=British Isles, FR=France, IP=Iberian Peninsula, MD=Mediterranean, AL=Alps, ME=Mid-Europe, EA=Eastern Europe, EM=East Mediterranean.*

According to Grillakis (2019), the Mediterranean region is among the most affected regions in SMI terms for the far future (>2060), with a 14.1% of decrease (increase in the % of SMI loose). For the medium-high scenario RCP6.0, the changes in the *Less intense* and *Moderate* SMI drought categories are expected to be similar to the RCP 2.6 scenario, or even milder in some cases at short-term (e.g., the Mediterranean). A strong increase in the *Extreme* SMI is also simulated in the second half of the 21st century for both the Mediterranean and the Alps (Table 1).

Table 1. *Change (in %) in the area fraction for each negative SMI category, for the near future (2020–2059) and far future (2060–2099) and the two radiative forcing scenarios.*

	2020 - 2059			
	RCP 2.6		RCP 6.0	
	MD	AL	MD	AL
Extreme	4.4	2.6	3.9	0.9
Severe	3.8	2.2	4.3	0.9
High	3.8	2.2	4.3	0.9
Moderate	0.3	1.1	1.0	1.0
Less intense	-1.0	0.6	-0.5	0.8

	2060 - 2099			
	RCP 2.6		RCP 6.0	
	MD	AL	MD	AL
Extreme	8.0	2.2	8.2	4.5
Severe	5.7	1.9	6.7	4.3
High	2.2	1.3	3.0	3.0
Moderate	-0.1	1.3	0.1	1.8
Less intense	-1.7	1.1	-1.8	0.8

Note: The changes in both futures are estimated relatively to the historical results (1966–2005). Legend: MD=Mediterranean (focused on Italy), AL=Alps. *Source: Adapted from Grillakis (2019).*

4. Climate change main risks

Key messages

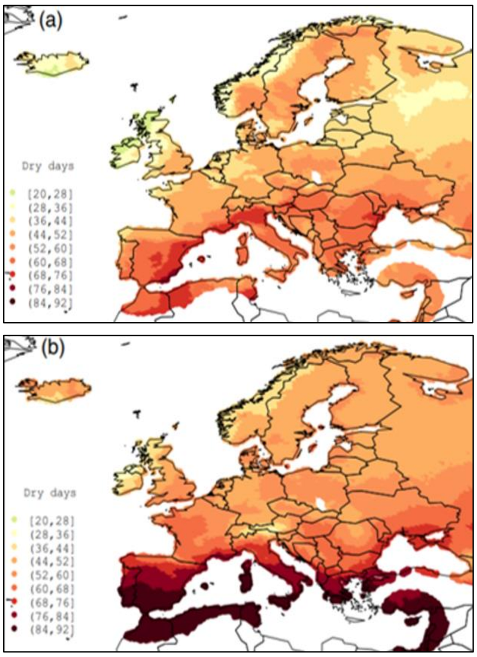
- ✓ General increases in the frequency, duration, and amplitude of heat waves are expected for all seasons.
- ✓ Droughts frequency will decrease or remain stable at current values of 1-2 episodes per year but their duration will notably increase up to 2 months in northern Italy.
- ✓ An increase in precipitation extremes is projected although wet days could substantially decrease in the summer season.
- ✓ The magnitude and frequency of winter and spring floods will increase, doubling the current tendency by 2050.

Changes in extreme weather regimes are one of the major concerns worldwide for being the cause of important risks and impacts on natural and anthropogenic systems. The assessment of weather extremes such as droughts, floods, and heat waves is generally of most relevance for society, economy, and stakeholders (EEA 2017b). The Special Report on Extreme Events (SREX) of the IPCC shows shreds of evidence of how Europe is particularly vulnerable to variations in the frequency and intensity of heat waves, persistent droughts, severe convective storms, and flash flooding. The main risks affecting the Muzza system are described below.

4.1. Dry days and dry spell

A dry day has been defined as an event in which daily precipitation values are below 0.1mm, while a dry spell is conceived as an episode of at least three consecutive dry days. Projections point out an overall increase in the annual number of dry days over Europe, particularly pronounced in southern Europe throughout seasons by 2071-2095 in line with Polade *et al.* (2014). For extreme dry days, regional hotspots evolve for higher global warming levels (e.g., for +1ºC warming), while a doubling of extreme dry days is detected in the Mediterranean (Vogel *et al.* (2020).

The assessment of dry days in southern Europe varies between 52–92 days depending on the season, although in northern Italy the interval will be between 44 and 76 days, being winter and autumn the driest seasons (Figure 22). However, the largest increases of dry days will be expected in summer and autumn by 2071–2095, considering an increase of about 10-15% (Table 2), enhancing heat wave episodes owing to the associated depletion of soil moisture (Ruosteenoja *et al.* 2018) and the subsequent reduced cooling effect via latent heat exchange, as occurred during the mega-heat waves of 2003 and 2010 (Miralles *et al.* 2014).



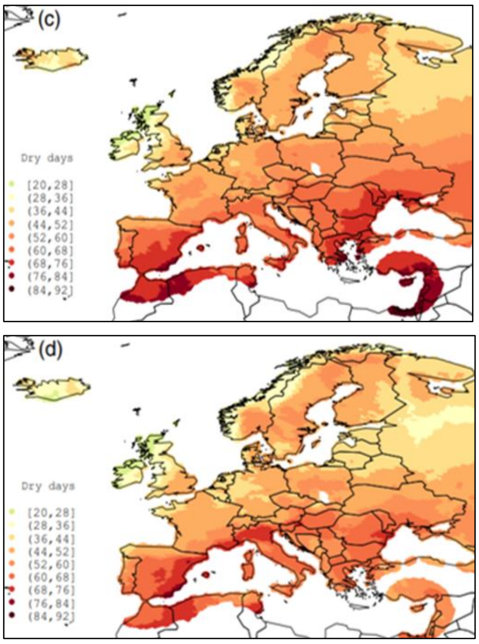


Figure 22. *Present number of dry days in (a) winter, (b) spring, (c) summer and (d) autumn. Source: Cardell et al. (2020)*

Table 2. *Average of the number of dry days in northern Italy for present and future projected periods and seasons.*

Winter

	Present	*Early*	*Mid*	*Late*
Value	51.82	51.91	52.52	53.19
SD	8.65	7.38	7.52	7.73

Spring

	Present	*Early*	*Mid*	*Late*
Value	52.84	52.94	53.98	55.32
SD	7.22	10.33	10.94	11.42

Summer

	Present	*Early*	*Mid*	*Late*
Value	53.36	55.37	57.86	62.24
SD	7.05	12.94	12.75	12.36

Autumn

	Present	*Early*	*Mid*	*Late*
Value	53.20	55.07	57.24	59.39
SD	8.35	12.44	13.82	13.22

Note: present observed (1981–2005) and early (2021–2045), mid (2046–2070), and late (2071–2095) future projected periods. SD=associated interannual standard deviation. Significant changes in the future distribution of dry days concerning the present period, at a 95% level of confidence, are underlined. Positive changes are quite consistent across models, while decreases present a low certainty according to the high SD. *Source: Adapted from Cardell et al. (2020).*

4.2. Warm days, tropical nights, and heat waves

The fraction of warm days, defined as the day in which the maximum temperature (T_{max}) is above the 95th percentile ($T_{max}95$) calculated from summer days of 1981–2005 baseline, could reach 59% of the whole summer in north-western Italy (Figure 23) due to an intensification of the anticyclonic circulation over the Mediterranean (Barcikowska *et al.* 2020). The study by Cardell *et al.* (2020), based on multi-model regional temperature averages over the European/Mediterranean regions for present observed (1981-2005) and different future projected periods until 2095 under the RCP8.5 scenario, provides an overview of warm days and heat wave projections for northern Italy (Table 3).

Future trends show that warm days will be more frequent by the late future projected period (2071–2095), including more than 30% of summer days. Moreover, the assessment of the interannual variations of warm days across seasons shows that there is a warming trend along the three future periods; the larger the expected changes the greater the interannual variations.

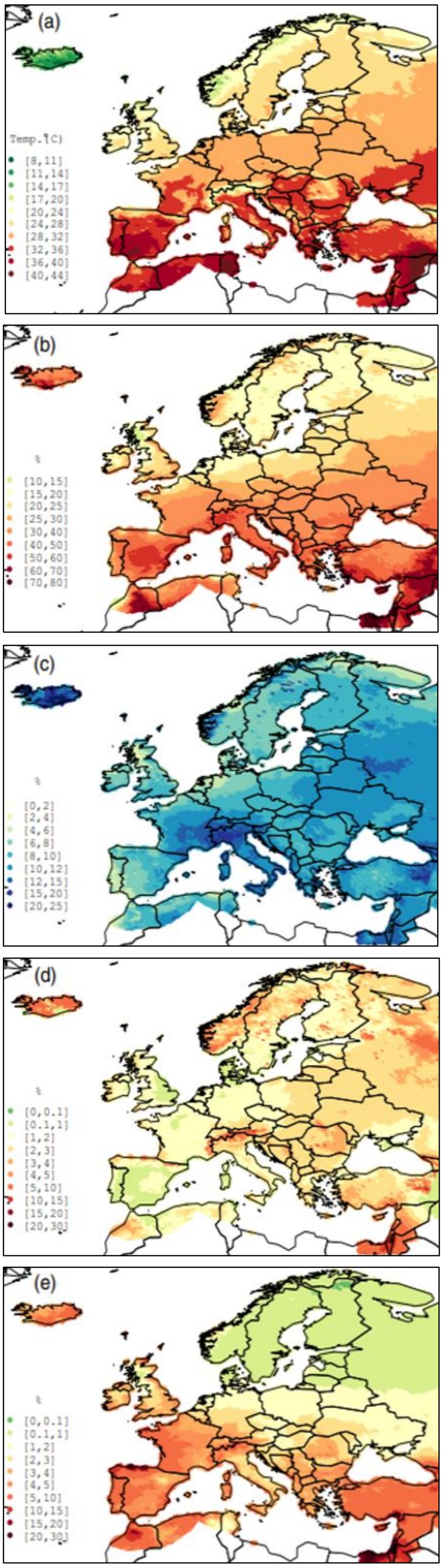


Figure 23. *Change in maximum temperature values regarding the present Tmax95. Note: (a) Present observed 95th percentile of daily maximum temperature in summer (T_{max}95; 1981–2005) used to define a warm day; (b) the future projected percentage of warm days in summer and (c) the corresponding inter-model SD; future projected percentage of warm days in spring (d) and (e) autumn. Source: Cardell et al. (2020).*

Table 3. *Average of warm days (in %) in northern Italy for present and future projected periods and seasons.*

	Present	*Early*	*Mid*	*Late*
Spring				
Value	0.06	0.32	0.75	2.25
SD	0.24	0.34	0.52	1.09
Summer				
Value	5.0	11.15	18.44	31.49
SD	5.69	3.01	4.61	5.89
Autumn				
Value	0.03	0.36	1.19	3.09
SD	0.13	0.35	0.79	1.41

Note: present observed (1981–2005) and early (2021–2045), mid (2046–2070), and late (2071–2095) future projected periods. SD=associated interannual standard deviation. Significant changes in the future distribution of warm days concerning the present period, at a 95% level of confidence, are underlined. *Source: Adapted from Cardell et al. (2020).*

Another notable factor is the rise in the number of tropical nights (nights during which the temperature remains above 20°C) and its combination with hot days (days with T_{max}>35°C and with daily mean temperatures exceeding the observed summer 90th percentile). The European Environment Agency mapped present and future conditions of both parameters, concluding a general increase in the number of combined tropical nights and hot days for 2021-2100, affecting Southern Europe (Figure 24). The Po Valley is no stranger to this trend, and by the mid-term (2021-2050), the number of tropical nights combined with hot days will pass from 18-30 (reference period 1961-1990) to more than 40, while at long-term the increase will pass the 50 tropical nights and hot days.

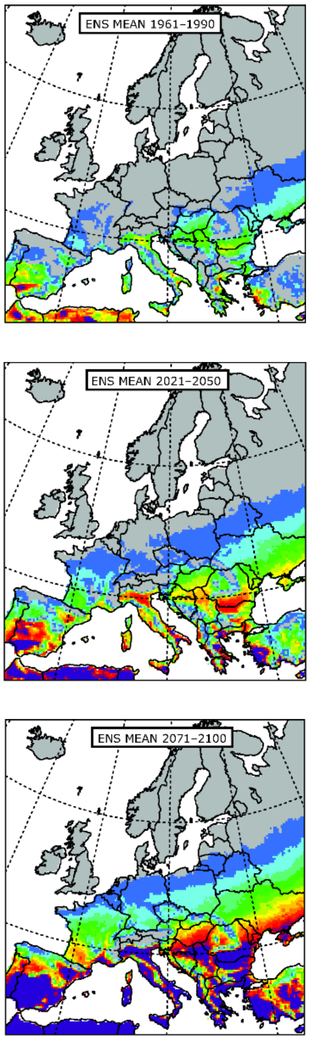
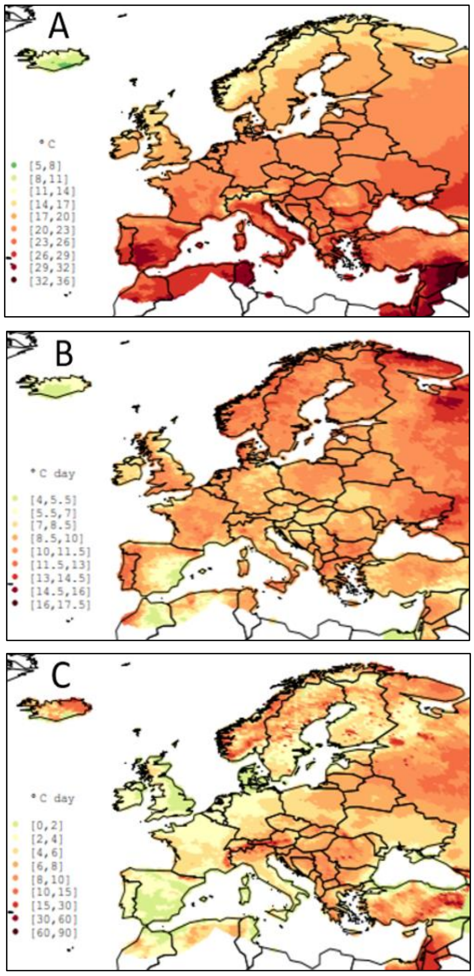


Figure 24. *Number of combined tropical nights and hot days. Note: reference period (top), mid-term (2021-2050) (middle), and long-term (2071-2100) (down).*

Heat waves can have different features and effects over a wide range of exposed human groups and areas and this made it difficult to stipulate a standard definition. However, heat waves have been characterized using several indices, commonly based on a certain period of consecutive days in which weather conditions are excessively warm (Perkins & Alexander 2013). According to the European Drought Observatory, a heat wave is an event of at least three consecutive hot days. Moreover, heat wave amplitude is the accumulated heat stress exceedance (ºC) for all days under heat wave conditions in a given time interval.

Several studies evidence an increased occurrence of summer heat waves along the 21st century (Meehl & Tebaldi 2004, Koffi & Koffi 2008, Abaurrea *et al*. 2018, Zhang *et al.* 2020). In line with previous findings (Amengual *et al.* 2014), general increases in the frequency, duration, and amplitude of heat waves are expected for all seasons by 2071–2095, although heat waves in northern Europe will be characterized by longer periods of relatively warm temperatures, while in southern Europe, heat waves will be shorter, but more acute and dangerous (Cardell *et al.* 2020). Concerning the spring, some areas of Italy will suffer an enhanced heat wave amplitude increase by the late 21st century (up to 60ºC day, Figure 25), while the largest positive changes will occur in the Alps (Table 4) and might be linked to a reduction in the snow cover and the snow-albedo effect (Gobiet *et al.* 2014).



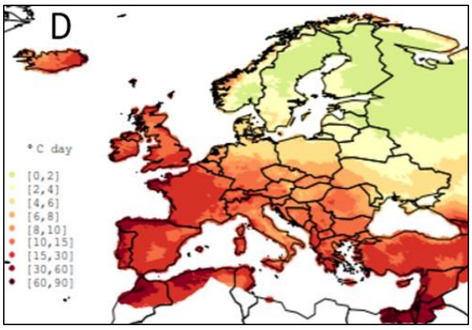


Figure 25. *Change in maximum temperature values regarding the present Tmax90. Note: (a) Present observed 90th percentile of daily mean temperature in summer (T_{mean}90; 1981–2005) considered for the definition of heat wave amplitude; (b) present observed heat wave amplitude in summer, (c) future change on heat wave amplitude in spring and (d) autumn. Source: Adapted from Cardell et al. (2020).*

Table 4. *Average of heat wave amplitude (in °C day) in northern Italy for present and projected periods.*

Spring

	Present	*Early*	*Mid*	*Late*
Value	0.02	<u>0.45</u>	<u>1.16</u>	<u>6.0</u>
SD	0.07	0.70	1.23	4.35

Summer

	Present	*Early*	*Mid*	*Late*
Value	9.06	<u>32.84</u>	<u>65.20</u>	<u>145.2</u>
SD	13.78	11.27	19.50	35.66

Autumn

	Present	*Early*	*Mid*	*Late*
Value	0.04	<u>0.74</u>	<u>3.06</u>	<u>10.81</u>
SD	0.18	0.84	2.41	5.44

Note: present observed (1981–2005) and early (2021–2045), mid (2046–2070), and late (2071–2095) future projected periods. SD=associated interannual standard deviation. Significant changes in the future distribution of heat wave amplitude concerning the present period, at 95% level of confidence, are underlined. Source: Adapted from Cardell *et al.* (2020).

4.3. Droughts

Once changes in the frequency of dry days have been assessed, a major concern arises in how droughts are expected to change under human-induced climate change. Drought is a recurring extreme climate event over land characterized by below-normal precipitation and is also often associated with warm temperatures over a period of months to years (Mishra & Singh 2010). Any consecutive period of dry days longer than three consecutive days (dry spell) is considered a drought. That is, a drought is a dry spell of length >95th length percentile of all identified dry spells in the present climate.

The influence of climate change on regional and local drought variability might be particularly significant across the Mediterranean Basin, which is one of the climate change hotspots while shows the highest drought frequency and severity from the early 1990s onwards (Samaniego *et al.* 2018). Droughts are affecting the Mediterranean region due to the strong interannual variability of precipitation, which is one of the most important characteristics of the Mediterranean climate (Lionello 2012). Meteorological drought is expressed as long-term deficiencies in precipitation only, while agricultural and hydrological drought deal with deficiencies in soil moisture, groundwater, and surface water reservoirs (Teuling 2013). Although the frequency of droughts is lower in the Mediterranean owing to their extremely extended length, future changes in the annual pattern indicate an increase in occurrence and severity over southern Europe by 2071–2095 (Vicente-Serrano et al. 2014).

However, patterns of the annual drought occurrence tend to be quite different depending on the region, showing positive or negative changes even in the same country (Caloiero *et al.* 2018). For example, in northern Italy the number of droughts will decrease or remain stable at current values of 1-2 droughts periods per year, although their duration will notably increase up to 2 months (considering the value) or 4 months (considering the SD), moving from 18-35 days to an interval of 66-110 days a year (Figure 26) (Cardell *et al.* 2020). Additionally, Table 5 shows how the number of droughts will decrease to half in the early period while it will increase significantly by the second half of the 21st century. Furthermore, the length of the droughts will move from the current length of 16 days a year to 65 days a year by the end of the century, an increase close to 300%.

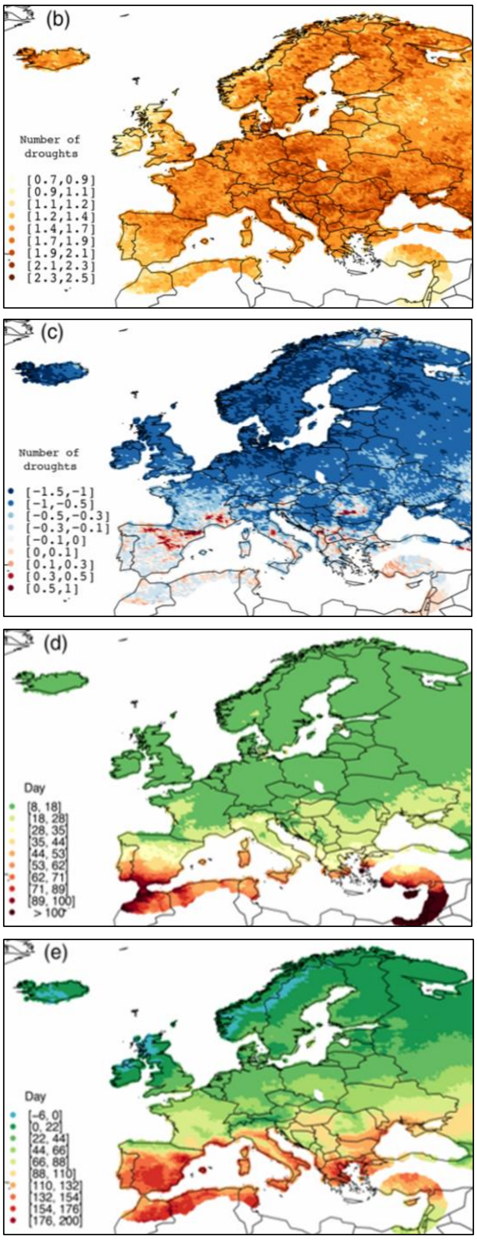


Figure 26. *Present and projected number and length of droughts. Note: (b) present observed number of droughts and (c) future change in the number of droughts. Also shown: (d) present observed mean drought length and (e) future change of this length. Source: Adapted from Cardell et al. (2020).*

Table 5. *Average of the number of annual droughts and drought length in northern Italy for present and projected periods.*

Number of droughts

	Present	*Early*	*Mid*	*Late*
Value	1.72	<u>0.78</u>	<u>0.90</u>	<u>1.11</u>
SD	1.18	0.56	0.57	0.51

Length of droughts

	Present	*Early*	*Mid*	*Late*
Value	16.31	<u>51.14</u>	<u>57.03</u>	<u>64.88</u>
SD	7.49	63.57	64.87	66.33

Note: present observed (1981–2005) and early (2021–2045), mid (2046–2070), and late (2071–2095) future projected periods. SD=associated interannual standard deviation. Significant changes in the number and length of droughts concerning the present period, at a 95% level of confidence, are underlined. *Source: Adapted from Cardell et al. (2020).*

4.4. Cold nights and cold spells

Regarding cold temperature extremes, a cold night has been defined as the event in which daily minimum temperature ($T_{\min}$) is below the observed winter 5th percentile ($T_{min}5$) from the baseline period (1981–2005). Besides, a cold spell is defined as an episode of at least three consecutive days with the daily mean temperature below 10th winter percentile, while cold spell amplitude is the accumulated cold stress exceedance (ºC day) for all days under cold spell conditions in a given time interval.

Future trends about cold nights under the RCP8.5 scenario show how a reduction of cold extremes is not so pronounced in central Europe and the Mediterranean as in northern Europe, exhibiting a future percentage of cold nights between 0.4-2%. However, some scattered areas of Italy will also undergo a strong decrease in the number of cold nights, passing from 5% of days in the present to 0.2% by the late future (Cardell *et al.* 2020). Moreover, the future percentage of cold nights would be significantly different concerning the present overall the regions from the mid-21st century (Table 6), by considering that the interannual variability is predicted to decrease despite the large expected change in the percentage of cold nights. On the contrary, cold spells will not be persistent in the Mediterranean because they will be associated with occasional cold polar intrusions, lasting only a few days.

Table 6. *Average of cold nights (in %) and cold spell magnitude (in ºC day) in northern Italy for present and future projected periods during the winter season.*

Cold nights

	Present	*Early*	*Mid*	*Late*
Value	5.0	2.75	1.30	0.56
SD	5.79	1.52	0.87	0.52

Cold spell magnitude

	Present	*Early*	*Mid*	*Late*
Value	19.97	11.74	6.63	2.18
SD	29.54	7.28	7.31	2.33

Note: present observed (1981–2005) and early (2021–2045), mid (2046–2070), and late (2071–2095) future projected periods. SD=associated interannual standard deviation. Significant changes in the future distribution of cold nights concerning the present period, at a 95% level of confidence, are underlined. Source: Adapted from Cardell *et al.* (2020).

4.5. Heavy precipitation

Heavy precipitation events are among the most threatening meteorological phenomena as they potentially induce high-impact subsequent effects. A heavy precipitation day has been defined as an event in which daily accumulated precipitation values are over the observed annual 95th percentile (*Precip*95), considering only the total number of days with daily accumulated precipitation ≥0.1mm (i.e., wet days). Therefore, heavy precipitation days quantifies extreme rainfall which can be directly responsible for floods and soil erosion.

Observations prove that this type of extreme events has intensified during the last decades over large parts of the world, including Europe (Fischer & Knutti 2016). Across Europe, intensifications have been observed throughout all seasons and most regions. According to Cardell *et al.* (2020), annual precipitation extremes are particularly significant in southern Europe with values above 40mm in some spots of areas of the Alpine region, where these heavy rainfalls account for an important fraction of the total annual amounts. In this line, Scherrer *et al.* (2016) documented significant intensifications through observed changes and past variations in the Alpine region –that is particularly prone to the impacts of heavy rainfall, such as the events in August 2005 in Switzerland, for example.

Models consistently project an increase in precipitation extremes in northern Italy (Table 7) throughout all the seasons and with the largest positive changes projected in winter, spring, and autumn by 2071–2095. However, Rajczak *et al.* (2013) suggest that the frequency of wet days is projected to substantially decrease in summer across the entire Alpine region, whereas in fall and spring substantial reductions are only projected for southern Alpine regions. Wherever, in winter, no clear changes in precipitation frequency are obvious. However, for some southern Alpine areas' projections suggest an increased number of wet days, which could be due to changes in atmospheric circulation (Faggian 2015).

Table 7. *Average of heavy precipitation days (in %) in northern Italy for present and future projected periods and seasons.*

Winter

	Present	*Early*	*Mid*	*Late*
Value	0.91	1.02	1.16	1.31
SD	0.03	0.02	0.02	0.02

Spring

	Present	*Early*	*Mid*	*Late*
Value	0.97	1.18	1.28	1.39
SD	0.04	0.02	0.03	0.03

	Present	Early	Mid	Late
Summer				
Value	1.59	1.64	1.69	1.64
SD	0.04	0.05	0.06	0.06
Autumn				
Value	1.54	1.72	1.83	1.97
SD	0.05	0.05	0.07	0.07

Note: present observed (1981–2005) and early (2021–2045), mid (2046–2070), and late (2071–2095) future projected periods. SD=associated interannual standard deviation. Significant changes in the future distribution of heavy precipitation days concerning the present period, at a 95% level of confidence, are underlined. Source: Adapted from Cardell *et al.* 2020).

In Europe, impacts from heavy precipitation are generally due to short-period rainfalls of localized convective activity in summer, and multi-day episodes of persistent large-scale precipitation in winter (Frei *et al.* 2006). Both kinds of events are projected to become more frequent and intense in large parts of Europe by the end of the 21st century (Ban *et al.* 2015). A heavy precipitation episode is an event of at least two consecutive days with daily accumulated precipitation above the observed annual *Precip*95 (in which only wet days are considered), duly characterized by their amplitude to determine whether this event will suppose a flood-related risk in the future.

Therefore, heavy precipitation amplitude is conceived as the accumulated rainfall stress exceedance for all the days under extreme wet conditions in a given time interval (Cardell *et al.* 2020). Projections point out an overall rise across seasons by 2071–2095 (Figure 27 & Table 8), except in some limited areas of the Alps. Likewise, heavy precipitation amplitude will substantially reduce by about 15mm day by the late 21st century in the Alpine area during the winter and up to 30mm day in autumn – although the high inter-model SD suggests poor confidence in this result.

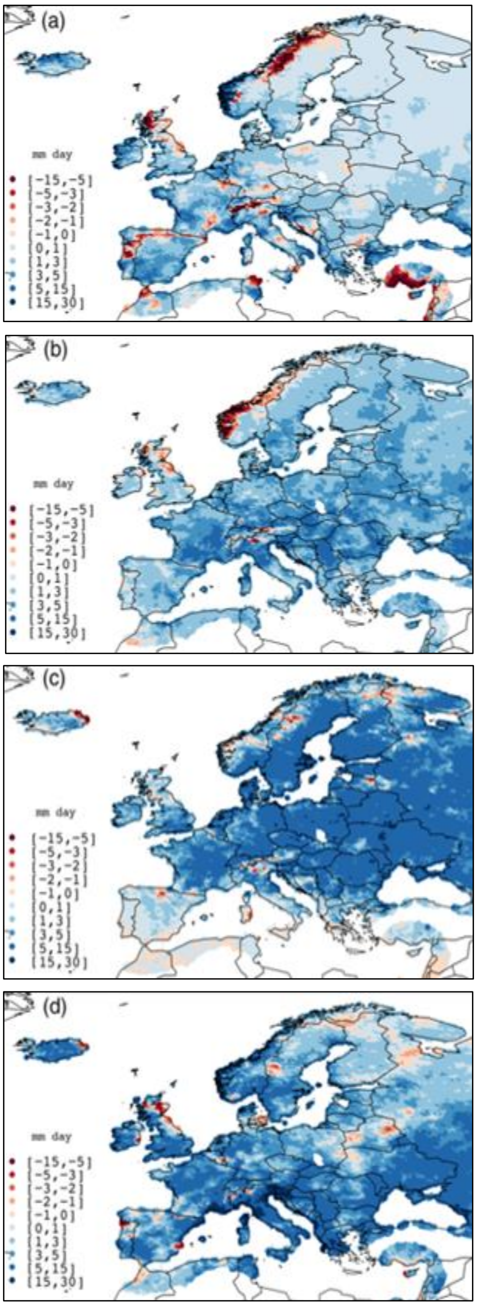


Figure 27. *Future change in heavy precipitation amplitude for (a) winter, (b) spring, (c) summer and (d) autumn. Source: Cardell et al. (2020).*

Table 8. *Average of heavy precipitation amplitude (in mm day) in northern Italy for present and projected periods and seasons.*

Winter

	Present	Early	Mid	Late
Value	2.65	2.54	3.82	4.40
SD	6.72	3.98	6.13	6.57

Spring

	Present	Early	Mid	Late
Value	2.47	3.62	5.35	6.19
SD	7.11	5.80	9.24	10.44

Summer

	Present	Early	Mid	Late
Value	5.75	8.42	11.87	11.72
SD	13.17	16.41	21.89	21.47

Autumn

	Present	Early	Mid	Late
Value	5.34	8.81	9.96	11.91
SD	11.35	16.63	22.16	23.95

Note: present observed (1981–2005) and early (2021–2045), mid (2046–2070), and late (2071–2095) future projected periods. SD=associated interannual standard deviation. Significant changes in the future distribution of heavy precipitation amplitude concerning the present period, at a 95% level of confidence, are underlined. *Source: Adapted from Cardell et al. (2020).*

4.6. Floods

It seems possible that the size and frequency of winter and spring floods will increase in Italy, and according to Faiella & Natoli (2019), it is estimated to raise significantly the probability of large floods in the long run. Consequently, their frequency will almost double by 2050 and triple by 2080, making Italy the country at the highest risk of flood in Europe after the Netherlands (Figure 28). This tendency will be more relevant in the north of the Alps and at altitudes up to 1,500m above sea level, where the return period of a current-day 100-year winter flood could be reduced to a 20-year event (EEA 2019). By contrast, summer floods are expected to occur less frequently in the future, although in the south of the Alps, floods are predicted to become more severe in all seasons except for summer.

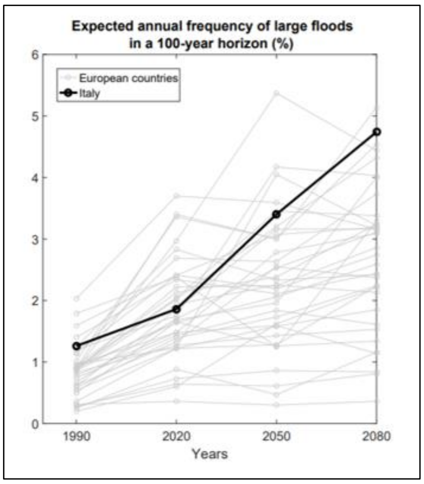


Figure 28. *Expected annual frequency of large floods in a 100-year horizon by European country. Legend: Black line: Italy; grey lines: the other 36 European countries in the sample. Source: Faiella & Natoli (2019).*

In northern Italy, the Po River basin is an area where the high level of human activity, the ongoing concentration and sensitiveness of assets, and the increase of unequally exposed people (Alfieri *et al*. 2016) have magnified the damages caused by floods. Because of its geomorphic and topographic settings and the complex drainage system articulation (Viero *et al*. 2019), this floodplain presents numerous areas prone to flooding, mostly located in the Piemonte, Lombardy, and Veneto regions (Roder *et al*. 2017). Moreover, the Po River has seen numerous floods in the recent and far past (middle ages), with an estimated 5-year return period (Coppola *et al*. 2014). According to a study by Zanchettini *et al*. (2008), who examined a 100-year long daily record of discharge observations, an increase of extreme events for floods has taken place in recent decades, although this was attributed to massive work done along with the river network rather than to climate change.

5. Climate change affecting agriculture

Key messages

- ✓ Reduced crop productivity due to an increase in extreme weather and climate events (droughts and heat waves).
- ✓ Increasing crop water requirements due to increased evapotranspiration rates.
- ✓ Extension of the seasonal activity of pests and diseases.
- ✓ Negative impacts on grassland productivity.
- ✓ Effects on the welfare and quality of livestock under heat stress for long periods of the year, with consequences on the productivity of the sector.

Understanding how climate change may affect agriculture is important to improve the management of climate change impacts and risks, and guide decision-making processes around possible adaptations to minimize damages and realize benefits. Climate change affects agriculture in several ways. Changes in temperature and precipitation as well as weather and climate extremes are already influencing crop yields and livestock productivity. Weather and climate conditions also affect the availability of water resources needed for irrigation (Konzmann *et al.* 2013) and livestock watering practices, by threatening the sustainability of the agricultural systems (Jacob *et al.* 2018).

According to both the *Special Report on Emission Scenarios* (SRES), focused on greenhouse gas emissions projections, and the *Representative Concentration Pathways* (RCPs), a consistent set of socioeconomic, technology, and biophysical assumptions, the IPCC agree on by the 2050s climate change will increase the risk of simultaneous crop failures if irrigation systems are not duly adapted to both water stress and surplus situations. Mediterranean region, which is a biogeographical, environmental, and historical unit, is among the global 'hot-spots' of climate change due to the expected warming and drying of the region (Pausas & Millan 2019) and the effects on the Mediterranean climate patterns (Figure 29) (Lionello & Scarascia 2018).

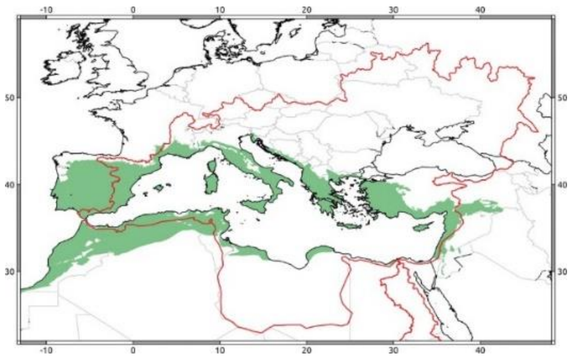


Figure 29. *The region with a Mediterranean climate (green) and the whole Mediterranean catchment (the thick red line). Note: Atmospheric processes occurring in the Mediterranean Sea can have hydrological implications in northern Italy. Source: Pausas & Millan (2019).*

The main high risks for the Mediterranean agriculture associated with global warming of 1.5ºC and 2ºC scenarios are heat and water stress, as well as droughts (EEA 2019), for which increasing water demand and risks for livelihood productions, as well as a decrease in crop yields, are projected (Figure 30).

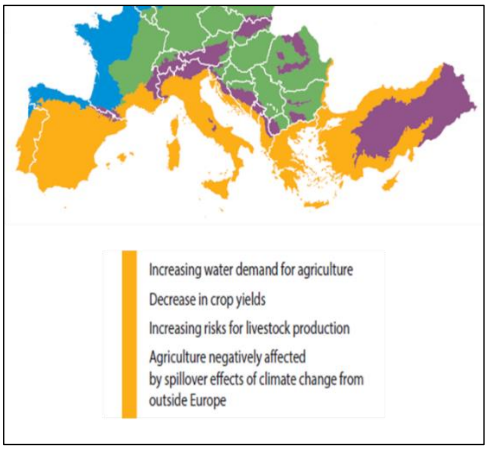


Figure 30. *Main climate change impacts affecting the Mediterranean agricultural sector.*

However, and according to Venkatramanan *et al.* (2020), global climate change will not only exacerbate the agricultural risks through their effects on crop ecology, crop geography, crop environment, and crop production, but also the agricultural resources and agricultural supply chain and commodity prices. In this line, the overall impacts of climate change on European agriculture could produce a significant loss for the sector: up to 16% loss in EU agriculture income by 2050 (EEA 2019).

The water-food-energy nexus (WEF nexus), which includes the synergies and trade-offs between water, energy use, and food production (Markantonis *et al.* 2019), will be strongly influenced by the projected increases in water demand from agriculture and energy sectors and the rising population (Gobin *et al.* 2017). In this respect, water demand will probably outweigh supply by 2050, unless alternative water management strategies and changes in food consumption (with implications for the types of crops grown) and energy preferences are implemented (EEA 2019). Moreover, adaptation at the farm level focus on technical measures that change production patterns, methods, farm structures, and strategies, could be used to address both the physical and socio-economic impacts of climate change.

5.1. Physical impacts

Summer heat wave events have increased since 1950, especially since 2000, and projections indicate a future warming trend in the Mediterranean area by the end of the 21st century. In 2018, a dry and exceptionally warm spring and summer was experienced in central and southern Europe (Figure 31). The most recent heat wave affecting northern Italy was in 2018 during the last 10 days of July and the first ten days of August, a period in which precipitation deviation was between 20-100% compared to the period 1981-2010 (Figure 32). Paradoxically, a reduction in crop yield can also derive from heavy precipitation events (EEA 2019).

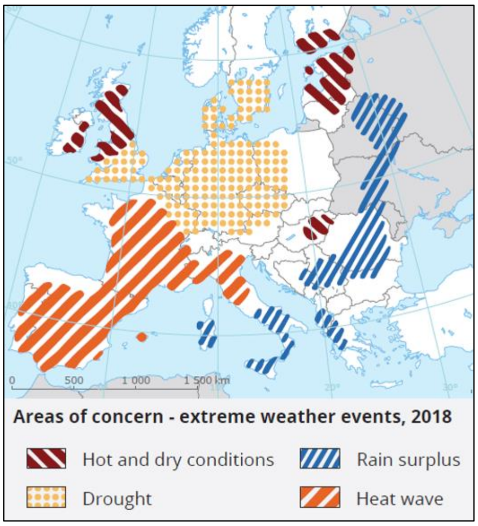


Figure 31. *Extreme weather events in Europe from July to September 2018. Source: EEA (2019).*

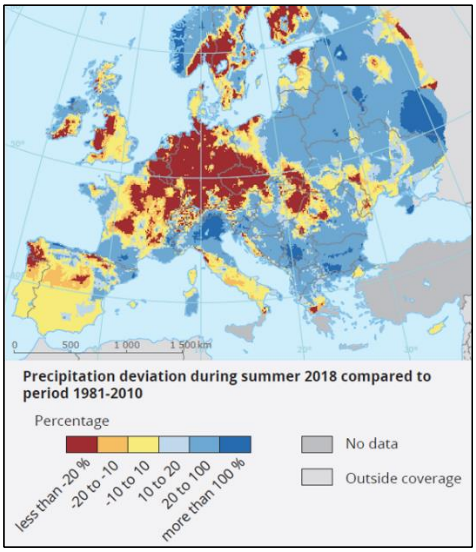


Figure 32. *Precipitation deviation during summer 2018. Source: EEA (2019).*

Heat stress can reduce plant photosynthetic and transpiration efficiencies as well as having negative impacts on root development, thus reducing crop yield (Lamaoui *et al.* 2018). Even short episodes of high temperatures (1-3 days of temperature >33°C) during sensitive crop growth phases (e.g. flowering and grain filling) can drastically reduce crop production, and prolonged periods of extremely high temperatures can even result in total destruction of the crop production (Moriondo *et al.* 2011). Extreme high temperatures during the reproductive stage can also negatively affect pollen viability, fertilisation, and grain or fruit formation

(Hatfield & Prueger 2015). Major effects of heat stress on wheat yield are related to a reduction in grain number because of sterility and abortion of grains (when the stress occurs during a period just before anthesis to at least 10 days after anthesis) and to reduced grain size due to cellular damage (Akter & Islam 2017). All these effects result in a significant reduction in grain yield (EEA 2019).

The recent analysis carried out for Europe as part of the Peseta IV project (Hristov *et al.* 2020) indicates for Italy, for the period 2030-2040 with the RCP8.5 scenario, a reduction of up to 25% compared to the current yields for irrigated corn, with fairly homogeneous results in the area, but possible increases in some central and northern regions (up to 25%). Results quite in line with those obtained from the simulations carried out by Mereu *et al.* (2019) on a European scale (in Figure 33 the detail for Italy is reported) for some varieties of wheat and maize.

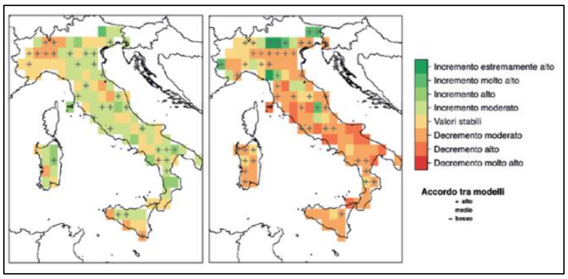


Figure 33. *Projections of variation (in %) of yield for soft wheat (left) and maize (right) in Italy for 2036-2065 with the RCP8.5 scenario. Note: Considered the most frequent class of yield variation thereafter simulation with 5 climatic models at 0.5 degrees of resolution (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M) from ISIMIP Project. Source: Adapted from Spano et al. (2020).*

However, Bocchiola (2015) also reported possible positive effects for rice in northern Italy, which highlights constant or increasing yields compared to the current both in the medium (2050) and in the long (2080) period, with the most moderate (RCP2.6 and RCP4.5), determined by the positive effect of the higher atmospheric concentration of CO_2 in offsetting the negative effect of climate change, even if in the face of greater water demand.

The increase in temperature may cause an acceleration in phenological development, with a reduced time for biomass assimilation and subsequently a lower crop yield (Gornall *et al.* 2010). Warmer temperatures determine an earlier start to active crop growth, faster plant development, and a potential extension of the crop-growing season, especially for perennial crops (Olesen *et al.* 2012). Episodes of high temperatures experienced during flowering and/or grain-filling phases can have large negative impacts on cereal grain yields (Rezaei *et al.* 2015). Projections of the timing of flowering and maturity data for future decades show an advancement of 1-3 weeks by 2050, with the largest changes observed for maize and the smallest for winter wheat (Yin & Leng 2020). Moreover, as climate change affects plant phenology and the time of flowering, the interactions between plants and pollinators may be disturbed, with detrimental consequences for crop productivity (Shrestha *et al.* 2018). Hailstorms cause damage to crops, being the Mediterranean area and the Alpine region those most vulnerable regions. Although future projections of hail events are subject to large uncertainties, some regional climate models suggest that the highest hail potential will affect mountain areas (Figure 34), such as northern Italy, the Alps, and the Po Valley (moving from 35 to 50 days in duration according to Mohr *et al.* 2015 and in a number of events according to Punge *et al.* 2017).

Furthermore, Baldi *et al.* (2014) calculated the annual hail event frequency distribution over the country at provincial and municipal scale (Figure 35), concluding that 1) the distribution is rather inhomogeneous both at municipal and provincial scale, 2) large areas like Po Valley are characterized by values lower than 0.5 events per year, and 3) north areas present values ranging between 1.5 and 2 annual events.

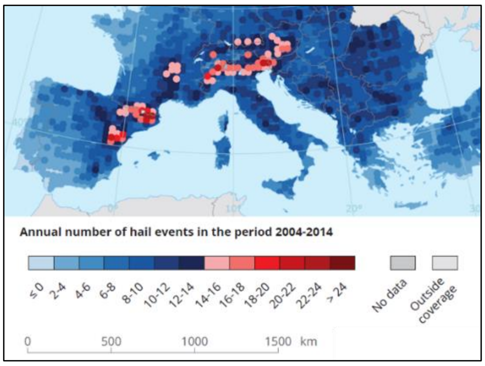


Figure 34. *Annual number of hall events in the period 2004-2014 in Southern Europe. Note: using overshooting cloud top detections per grid cell and average, 0.3°x 0.5. Source: Adapted from Punge et al. (2017).*

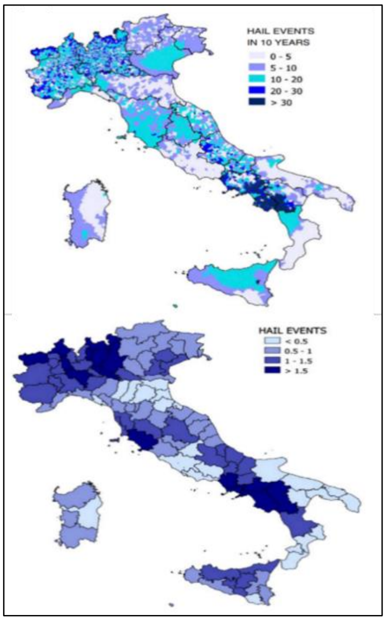


Figure 35. *Distribution of hail events by decades at municipality scale (top) and yearly at provincial scale (down).*

The time series of the potential hail index could present high annual and multiannual variability. For example, around Milan in northern Italy, where the convective potential is highest according to the Mohr *et al.* (2015) analysis, mean potential hail index values range between 18-60 days (mean 40 ± 10 days) between 1950 and 2010 (Figure 36).

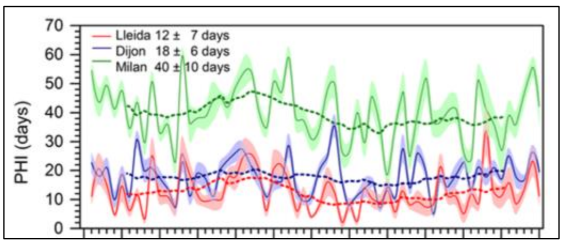


Figure 36. *Time series of the annual potential hail index for different locations between 1950 and 2010. Note: Values (mean solid ± SD).*

Moreover, Mohr *et al.* (2015) examined how representative could be an area regarding the time series by correlating the annual potential hail index values with those of all grid points in the extended area (e.g. Milan location vs. Po Valley area) (Figure 37). The results show how around the indicated location, the Spearman rank correlation coefficient *r* is very high ($r \geq 0.9$), which means that the potential hail index is representative for a large area (i.e. around 100–150 km).

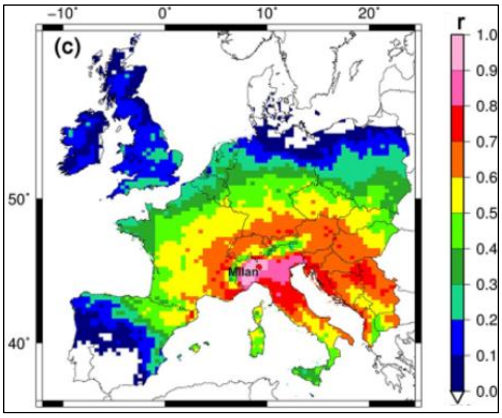


Figure 37. *Correlation coefficient between the annual potential hail index for Milan area location. Source: Adapted from Mohr et al. (2015).*

Droughts generally originate as a meteorological phenomenon, in which periods of low precipitation may produce water scarcity in various parts or the whole of the hydrological cycle, which in turn affects crops and various environmental systems (Tramblay *et al.* 2020). Long and/or intense droughts during the rainy season can have serious consequences for crop production and agricultural revenues. The lack of soil moisture is at the forefront of drought issues, as it affects crop growth and yields, and is thus called agricultural drought. Soil moisture is a fundamental variable, acting as a switch and integrator of various water fluxes interlinked in the soil-vegetation-atmosphere system and regulating energy flows and biogeochemical cycles, playing a key role in plant growth (Gray & Brady 2016).

Historical trends report that drought frequency and severity increased over the Mediterranean area over the period 1950-2015 (Spinoni *et al.* 2018). However, more recent episodes have been identified for northern Italy and the Alps region. For example, in July 2017, the European Drought Observatory (EDO) published an analytical report on the severe drought that affected half of Italy's regions (most of them north located, such as Lombardy or Veneto), being one of the country's driest springs in 60 years, with some regions reportedly receiving 80% less total rainfall than normal. The main effect for the Po Valley was the soil moisture anomaly (Figure 38), which is used as a direct measurement of the water availability for plants. More recently, in August 2019, another drought episode affected the region, generating vegetation stress and soil moisture deficit alerts but also rainfall deficit alerts in some parts of the Po Valley (Figure 39). In June 2020, another analytical report (EDO 2020) highlights how earlier in the spring, drier than usual conditions were experienced across central Europe as well as in northern Italy, in which a widespread lack of rainfall in April based on a precipitation anomaly has been recorded (Figure 40).

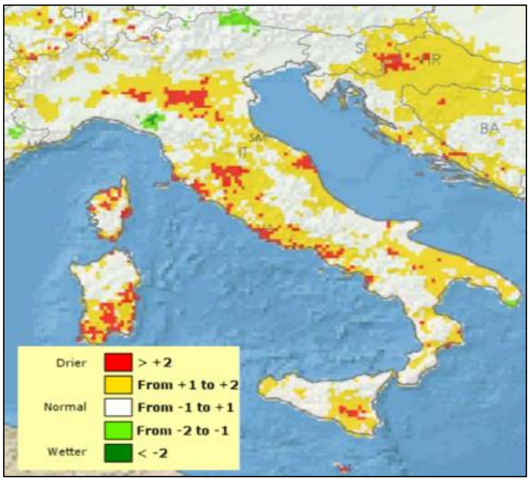


Figure 38. *Soil moisture anomaly across Italy, 2nd "dekad" (10 days), July 2017. Source: Edo (2017).*

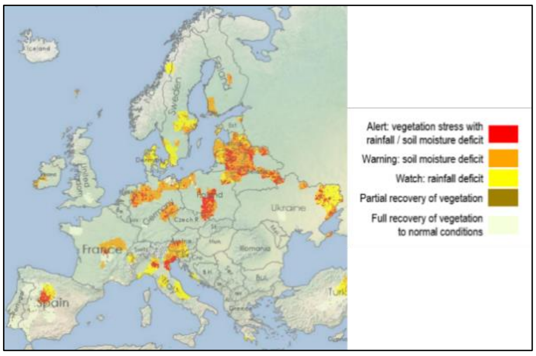


Figure 39. *The Combined Drought Indicator (CDI) for the second dekad of July 2019. Note: The CDI is based on the analysis of precipitation, soil moisture, and the fraction of Absorbed Photosynthetically Active Radiation (fAPAR), to identify areas that are at potential risk to suffer drought, areas where drought manifests through a significant soil moisture deficit, and areas where vegetation is already affected by drought conditions. Source: EDO (2019).*

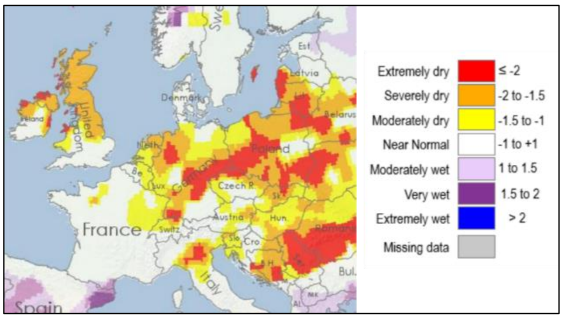


Figure 40. *Standardized Precipitation Index (SPI), showing the precipitation anomalies concerning the long-term climatological average. Source: EDO (2020).*

Among the regions expected to experience the largest drought frequency highlight the southern and central Europe, including northern Italy and the Po Valley in which more than one event per decade is projected, although without a marked extreme or severity nature (Figure 41) and mostly affecting the summer and the spring seasons (Figure 42).

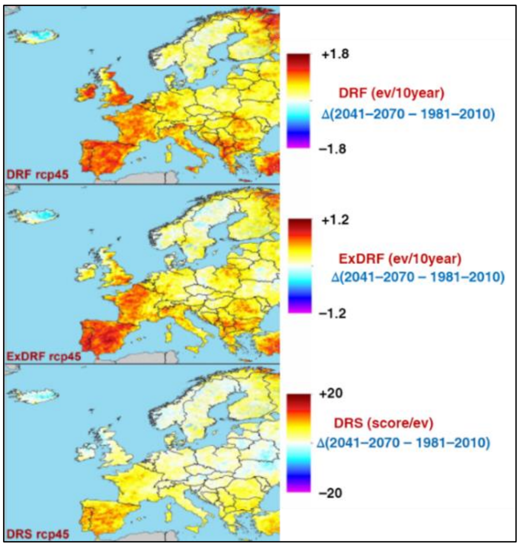


Figure 41. *Difference of drought frequency (top), extreme drought frequency (middle), and drought severity (down) between the near future (2041–2070) and the recent past (1981–2010). Note: averaged over the 11 simulations and computed at a 12-month accumulation scale referred to RCP4.5. Source: Adapted from Spinoni et al. (2018).*

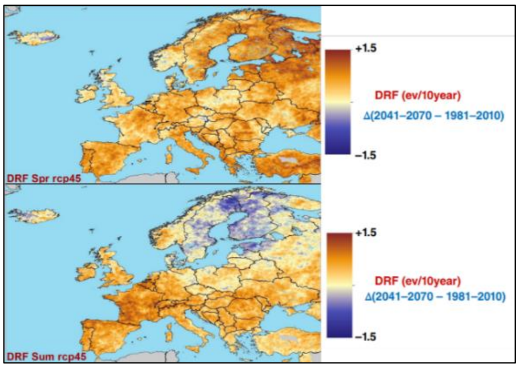


Figure 42. *Difference of drought frequency between the near future (2041–2070) and the recent past (1981–2010) for spring (top) and summer (down). Note: averaged over 11 simulations under RCP4.5 and computed at a 3-month accumulation scale. Source: Adapted from Spinoni et al. (2018).*

Summer and autumn droughts show an increase over southern Europe, while it is worth noticing that, including mountainous areas (e.g. the Alps), summer drought increase is very robust, as at least nine simulations at latitudes south to the Alps projected simultaneous increase of frequency and severity of droughts (Figure 43). Moreover, and especially for RCP8.5, the Alpine region is found to experience stronger drought differences regarding frequency between the present and future decades than surrounding regions (Figure 44). As projected by Spinoni *et al.* (2018), the Alpine region could suffer an increase of more than 50% and one more event by decade in drought frequency values registered before 2010 and especially locate during the summer and the spring seasons.

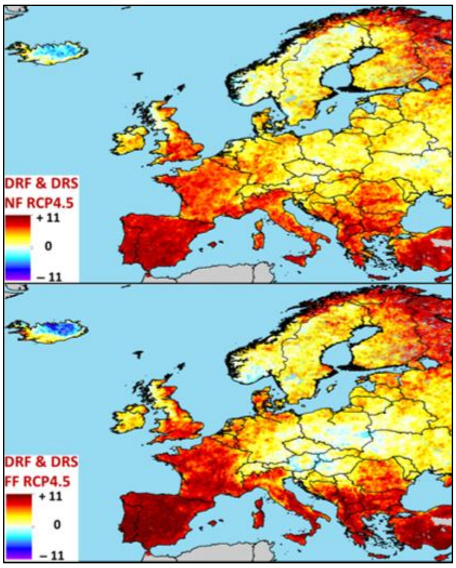


Figure 43. *Number of simulations indicating contemporary increase (positive values) or decrease (negative values) of drought frequency and severity at annual scale in near (top) and far future (down) referred to RCP4.5. Source: Adapted from Spinoni et al. (2018).*

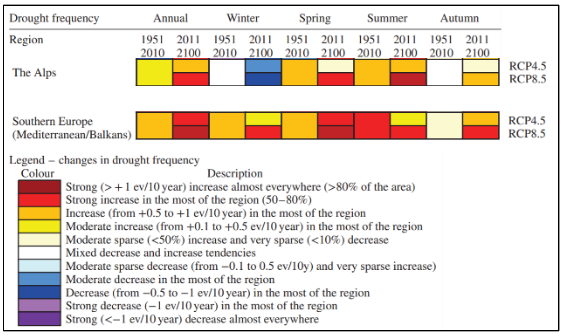


Figure 44. *Summary of annual and seasonal drought frequency trends from 1951 to 2100 for the Alpine region and the Mediterranean.*

Drought patterns will increase the pressure on water resources, especially during the crop growth stage. Irrigation demand for water for the Mediterranean area is projected to increase between 4%-18% by the end of the 21st century (for RCPs 4.5 and 8.5 climate scenarios, respectively) (Cramer *et al.* 2018), increasing the conflicting demands for water by different sectors (e.g. agriculture, industry, citizens).

On the contrary, excess precipitation events (including flooding and water stagnation) can lead to crop damage and soil erosion in agricultural fields. This could be perceived as a problem in the Alpine regions and the Mediterranean mountains, especially for winter wheat and spring barley, and for cereal fields in the Pannonia region. Furthermore, excessively wet soils (Figure 45) can change moisture trends and directly damage crops (Feng & Zhang 2016), due to anoxic conditions, increased risk of plant disease and insect infestation, and delayed planting or harvesting because it is not possible to operate machinery (EEA 2019).

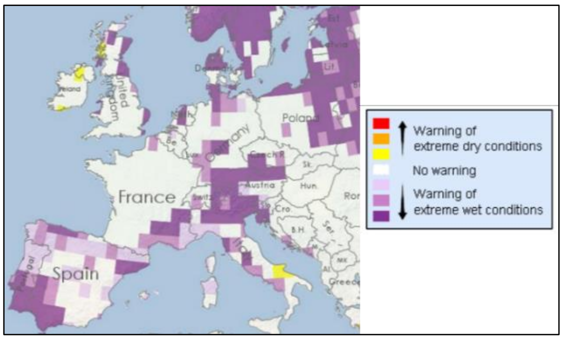


Figure 45. *SPI forecast for June to August 2020 (SPI-3), based on ECMWF S5 ensemble forecasts. Source: EDO (2020)*

According to Perpiña *et al*. (2018), in the period 2015-2030, the incremental agricultural land abandonment in EU-28 is projected to reach around 4.2 million ha (i.e. about 280 thousand ha per year on average). This will bring the total abandoned agricultural land to roughly 5.6 million ha, equal to approximately 3% of the total agricultural land (183.6 million ha) in 2030. Considering that the decrease of EU agricultural land over the same period is estimated to about 1%, this would be an alarming trend. Moreover, although the estimated potential risk of agricultural land abandonment for 2030 is (very) low (i.e. less than 2%) in northern Italy (Figure 46), the agricultural land abandonment projected for the whole country is about 456 thousand ha (3.4% over the total utilized agricultural area).

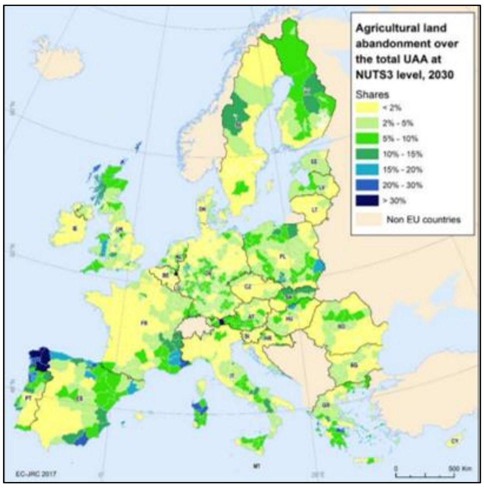


Figure 46. *Shares of agricultural land abandonment concerning the total agricultural land aggregated at NUTS 3 level in 2030*

Climate change is however also associated with greater pest pressure (Deutsch *et al.* 2018). Distribution ranges of pest species are expected to shift, to the detriment of cropping systems (Olesen *et al.* 2011), because climate change is likely to extend the seasonal activity of pests and diseases and cause an increase in their occurrence, especially in cooler regions where warmer temperatures may permit more reproductive cycles of insect pests, such as in the perimeter of the mountain areas (e.g., the Alps) (Grunig *et al.* 2020). Furthermore, climate suitability for pest occurrence will be higher in small grain cereal crops, particularly wheat and barley which are dominant in most agricultural plains, such as the Po Valley (Svobododà *et al.* 2014).

Climate change also affects livestock systems directly and indirectly. Livestock is affected directly through effects on animal health and welfare. For instance, heat stress affects animal health and welfare and can lead to reduced milk production and reproductive efficiency (EEA 2019).

Lastly, climate change could intensify a climate zone migration for the whole of Europe, starting from a shift in agro-climate zones across southern Europe over the past 40 years (Figure 47). For example, in the Po Valley, the

Pannonian climate has been replaced by the Maritime South climate by lengthening of the growing season and an increased active temperature accumulation.

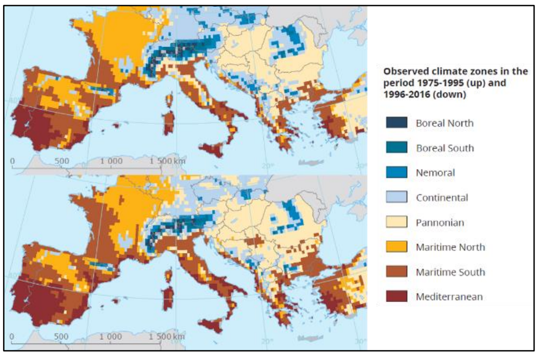


Figure 47. *Climatic zones based on the climate data in the period 1975 1995 (top) and in the period 1996 2016 (down). Source: EEA (2019) based on Ceglar et al. (2019).*

5.2. Socio-economic impacts

Climate change can, directly and indirectly, impact agricultural production and the agro-ecosystems –conceived as systems composed of physical, biological, and socioeconomic subsystems that interact within the framework of human-led agricultural processes (León *et al.* 2018). Direct impacts relate to changes in phenology and calendars, displacement of cultivation areas and soil loss, changes in water supply and irrigation demand, and direct effects of increased levels of CO_2 on growth. Indirect effects are those that arise as a result of direct effects that can have further negative impacts on agricultural production (e.g., increases in pests, diseases, invasive species, and extreme events, such as very strong winds, hailstorms, intense heat, and frosts). Consequently, there is a cascade of impacts from climate change (Figure 48) that affect agroecosystems and agricultural production, influencing the price, quantity, and quality of products, and consequently the food security of the whole system (Ray *et al.* 2019).

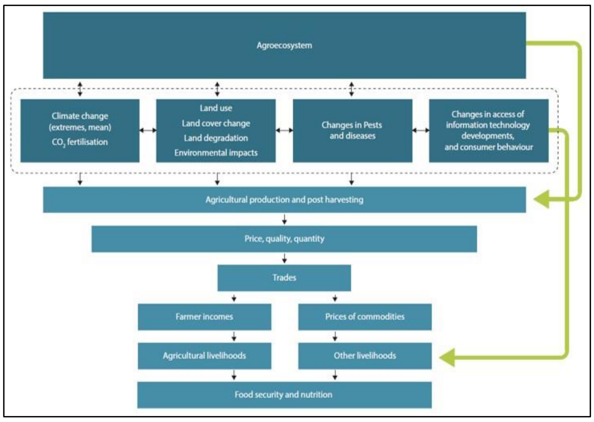


Figure 48. *Schematic representation of the cascading effects. Note: The green arrows represent direct impacts of changes in agroecosystems on agricultural production (through, for example, changes in agricultural practices) and impacts of drivers on livelihoods. Source: EEA (2019).*

In parallel, this can spread across the whole economy of the agricultural sector with macro-economic effects on food prices and farm incomes to ensure the availability, access, utilization, and stability of food supply over time as the four pillars of food security (Calicioglu *et al.* 2019). Indirect effects are usually measured with indicators of economic performances, gross domestic product (GDP), and metrics measuring producers' and consumers' attitudes and profiles (Cappelli *et al.* 2020), which can result in changes in the profitability of agricultural production and the share of income spent on food (EEA 2019). Figure 49 shows the relative importance of the climate impacts across the EU regions according to the welfare losses (% GDP) in the high warming scenario. As one moves south impacts appear to be higher as a share of GDP, confirming a north-south division for agriculture, labour productivity, and river floods.

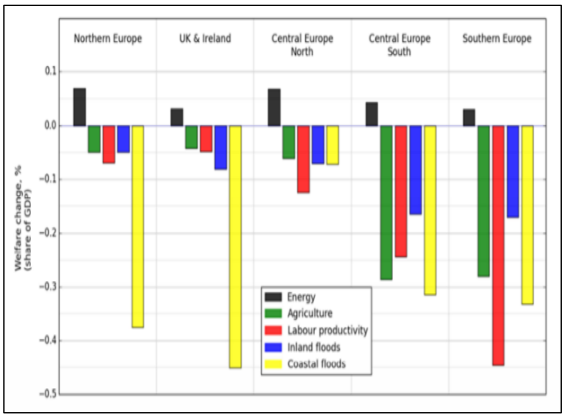


Figure 49. *The geography of impacts for the high warming scenario (without health impacts) regarding the welfare losses (% of GDP). Source: Circal et al. (2018).*

However, profitability can be also measured in terms of farm and land value. Farms in southern Europe (including northern Italy) could suffer land value losses up to 9%, while the farmland value could decrease by more than 80% by 2100 (EEA 2019). Moreover, two-thirds of the loss in land values at European level could be concentrated in Italy, where the revenues of Italian farms are very sensitive to seasonal changes in climate parameters (Bozzola *et al.* 2018). Although the projections show that Italy has the largest aggregate loss of farmland value, ranging from EUR 58 billion to EUR 120 billion by 2100 (34-60% decrease) (Figure 50), these estimations are based on Ricardian analyses, which do not account for technological and policy changes and represent the climate change impacts statically –that is, not accounting for unprecedented extreme weather and climate events that may occur in the future (De Salvo *et al.* 2014).

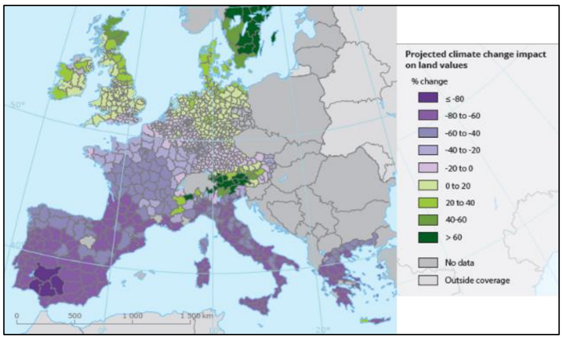


Figure 50. *Percentage change in farmland values projected for the period 2071 2100 compared to 1961 1990. Note: The map combines the impacts of three different climates predicted by General Circulation Climate Models (GCMs): Hadley CM3, ECHO-G, and NCAR PCM, all of them based on the A2 SRES. Source: EEA (2019) based on previous work by Van Passel et al. (2017).*

Moreover, the negative impact of soil erosion on crop productivity is mostly experienced by Mediterranean countries, included Italy, and particularly affects rice and wheat, as these are the dominant crops in the region (Panagos *et al.* 2018). When the physical impacts are translated into economic terms, Italy presents very high economic losses even though is less affected than other countries in physical terms (Figure 51). Moreover, Italy is almost three times less affected than Slovenia but economic losses are higher because a greater proportion of the country's land is subjected to severe erosion (33%).

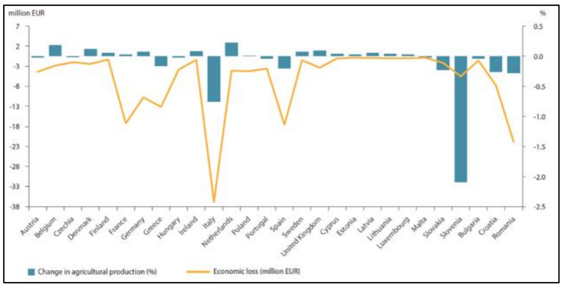


Figure 51. *Changes in agricultural production and economic losses in the EU due to soil erosion. Note: The figure shows changes in agricultural production in percentages and GDP (million euros) in 2020 (compared with 2010) across European countries due to soil erosion, showing differences between direct and indirect effects. Source: EEA (2019) based on Panagos et al. (2018).*

In the same line, crop producer prices are expected to vary between -3% for cereals and +5% for other arable field crops in a warming scenario of +2ºC by 2050, consistent with a high-end RCP8.5 emission scenario (EEA 2019). Introducing the CO_2 fertilisation effect is assumed to trigger greater competition on the world markets, increasing domestic production, but it may instead lead to a price decrease for all agricultural commodities (e.g. 20% decrease in the cereal price) (Ciscar *et al.* 2018). Livestock and livestock commodities are also affected both directly, through the variation in productivity and yields, and indirectly, through variations in feed prices and trade (Ciscar *et al.* 2018). High temperature and air humidity during breeding increased cattle mortality risk by 60% in Italy (Crescio *et al.* 2010).

Severe droughts have also traditionally caused considerable socioeconomic losses in agriculture, both in rainfed and irrigated lands, generating significant reductions in crop production (Ding et al. 2011). Since the 1960s, drought events have been one of the main drivers of crop failure globally (Cottrell *et al.* 2019), affecting the world economy and food security. For example, the 2003 European summer heat wave in combination with the antecedent prolonged drought period, caused a wide crop shortfall in most regions of southern Europe of a compound cost of almost EUR 15 billion (García-Herrera et al. 2010). In summer 2017, record temperatures and a long period without rain created a relevant phenomenon of water scarcity in Italy. As a consequence, the state of emergency was declared including 11 of the 20 regions, from Lombardy in the north to Sicily in the south. In late 2018, northern and central Europe experienced an extensive heatwave and drought (temperatures were much higher than the 1981–2010 average from April to December, with a mean temperature anomaly of +2.5ºC) (Thompson *et al.* 2020). According to the media, the 2017-2018 drought has caused the most severe problems to the EU vegetable sector in the last 40 years (Euractiv 2018).

Regional damages depend on the combined effect of the agricultural land regional use (crop mix), the amount of drought-affected areas, but also on factor mobility and trade relationships between regions (Ault 2020). For example, Garcia-Leon *et al.* (2021) calculated the direct effect on agricultural output due to different droughts periods (Figure 52). In 2003, it was estimated a decrease in agricultural output of -3.74% (equivalent to €2.06 billion), being the northern regions (highlighting the Lombard region in 2006) most affected. Their estimations indicate that the total damages caused by agricultural droughts in the Italian economy (also considering food manufacturing industries) can range from 0.01-0.10% of Italian GDP, that is, between approximately €0.55 and €1.75 billion. According to the farmers' association Coldiretti, the 2017-2018 drought caused losses to the agriculture sector of at least €2 billion, coinciding with the worst scenario identified by Garcia-Leon *et al.* (2021).

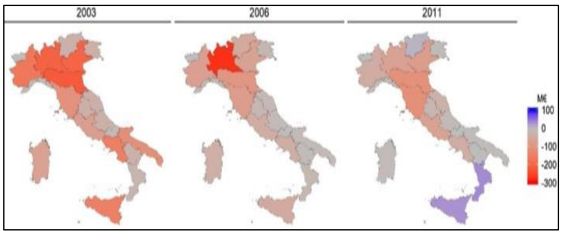


Figure 52. *Regional variation of the Italian GDP (in € million) in response to agricultural drought shocks at the three scenarios: 2003, 2006, and 2011. Note: Solar years 2003, 2006, and 2011 were studied as extreme, moderate, and mild dry years, respectively. Source: Garcia-Leon et al. (2021).*

Although the expected increase in the frequency and intensity of droughts and their corresponding economic impact, river flooding is the costliest natural disaster in Europe (Dottori *et al.* 2020). In Italy, floods have been among the most destructive climate-related catastrophes (Figure 53). For example, the October 2000 extreme precipitations event is amongst the most significant that have occurred in northern Italy over the past decades, leading to numerous inundations and landslides. Economic damages of over 2.5-8.6 billion euros were reported by different databases (Carrera *et al.* 2015), while the flood caused serious damages to agriculture affecting livestock, crop production, farm structures, and farming facilities (Farinosi *et al.* 2012). According to the CMCC Foundation (2015), the expected annual output losses are projected to increase from 164 million euros in the 2000s to 204 million euros (constant 2004 prices) in the 2080s. The distribution of losses is uneven across the country: The north bears 50% of total losses, highlighting Lombardy (around 24 million euros, 14% of national losses) and Veneto with around 20 million euros (12% of national losses). Furthermore, in the 2080s Lombardy is projected to have the highest expected annual output losses (34 million euros, 17% of national losses, that is, 44% increase by the 2080s).

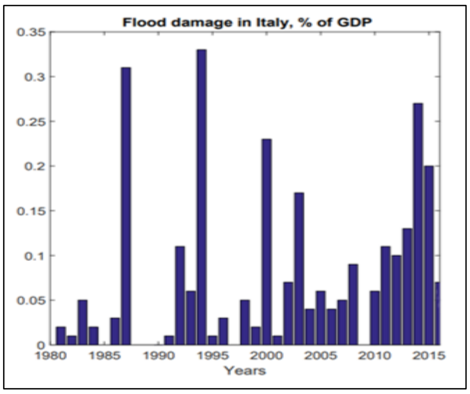


Figure 53. *Flood damage in Italy as a percentage of GDP (1980-2015). Source: Faiella & Natoli (2019).*

Flood risk management has been the concern of agricultural policies by focusing on land drainage (i.e. the removal of problems caused by the excess of water on/in the soil), of which flood protection was a critical part (Scorzini & Leopardi 2017). However, although agricultural areas in the floodplains are highly vulnerable to floods, when comparing total loss figures after flood events, damage to the agricultural sector is frequently estimated as considerably lower than that of urban areas (Scorzini *et al.* 2021). In contrast to other sectors, as the residential one, crop damage depends on many hazards parameters: apart from the usual variables that can be easily derived from hydraulic modelling, like water depth and flow velocity, other influencing factors are the presence of sediments and/or contaminants, inundation duration, the salinity of water and, most importantly, the timing (monthly) of the flood, due to the seasonality of crop production and susceptibility of the plants at different vegetative stages (Molinari *et al.* 2019).

These parameters are included in most of the damage models for crops, both in process-based simulations –operating with a daily time step to calculate various crop and soil properties– and statistical simulations –based on observations of weather and crop yields to relate the former to the latter– (Lobell & Asseng 2017). However, only some models tend to consider 1) adaptation strategies and attitudes (Figure 54) and 2) the behaviour of farmers after the occurrence of the flood (e.g. the decision to abandon the production or to continue with increasing production costs), which has been shown to strongly influence the damage sustained by the farm (Holstead *et al.* 2017).

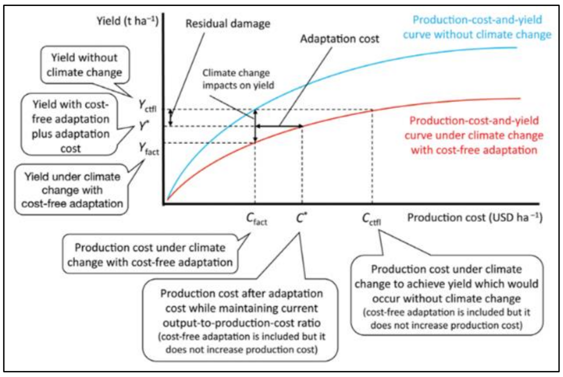


Figure 54. *Production cost, decadal mean yield, adaptation cost, and residual damage. Note: The production cost and yield curves are computed for each country and socioeconomic scenario considered. Source: Iizumi et al. (2020).*

According to the National Mosaic of Flood Hazard Zones realised in 2017 by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA 2018), the high flood hazard zones –return period of 20-50 years, frequent floods– in Italy amount to 12,405 km^2 (4.1% of the territory) and about 2 million inhabitants (3.5%); the medium flood hazard zones –return period of 100-200 years– to 25,398 km^2 (8.4% of the territory) and about 6 million inhabitants (10.4%), and the low hazard zones –low probability– to 32,961 km^2 (10.9% of the territory and about 9.3 million inhabitants (15.7%) (ISPRA 2018). The Po Valley regions (Piemonte, Lombardia, Veneto, and Emilia-Romagna) concentrates the highest percentage of medium flood hazard zones (83.2%, 16,437.6 km^2) while being four of five regions with more resident population exposed to flood risk (Figure 55).

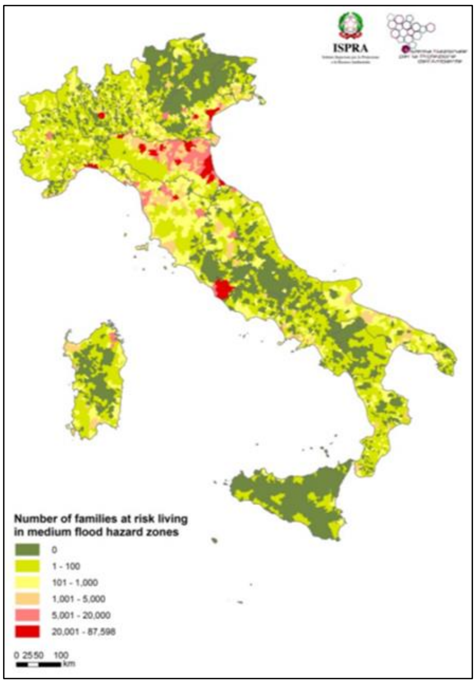


Figure 55. *Population at risk living in medium flood hazard zones on a regional and municipal basis. Source: ISPRA (2018).*

Flood risk reduction strategies in line with the EU Floods Directive (Directive 2007/60/EC) can substantially reduce the projected increase in flood risk with global warming. In particular, reducing flood peaks using retention areas shows strong potential to lower impacts in a cost-efficient way in most EU countries, including Italy, in which the expected annual damages could be reduced in a half (Figure 56).

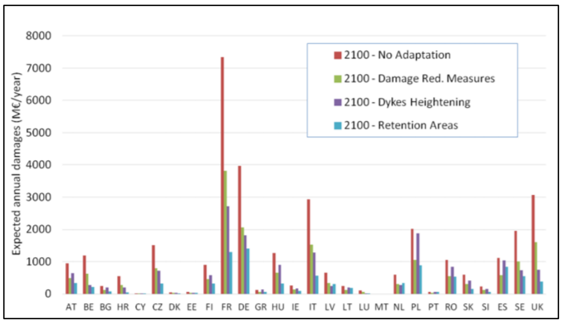


Figure 56. *Comparison of expected annual damages (M€/year) in 2100 assuming no adaptation, and with the implementation of three different adaptation strategies. Note: Results are calculated assuming a 2°C warming scenario. Source: Dottori et al. (2020).*

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