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Climate change and Europe's water resources

JRC PESETA IV project – Task 10

Bisselink B., Bernhard J., Gelati E., Adamovic M., Guenther S., Mentaschi L., Feyen L., and de Roo, A.

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Joint Research Centre

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Contact information
Name: Ad de Roo
Address: Joint Research Centre, via E. Fermi 2749, 21027 Ispra (VA), Italy
Email: Ad.DE-ROO@ec.europa.eu
Tel.: 0039-0332-786240

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Contents

Executive summary

In addition to the already existing pressure on our freshwater resources, climate change may further decrease water availability. In this study, projections of future water resources, due to climate change, land use change and changes in water consumption have been assessed using JRC's LISFLOOD water resources model.

The results presented are based on 11 climate models which project current and future climate under two Representative Concentration Pathways (RCPs): RCP4.5 and RCP 8.5 emission scenario. RCP4.5 may be viewed as a moderate-emissions-mitigation-policy scenario and RCP8.5 as a high-end emissions scenario. A 30-year window around the year that global warming reaches 1.5°C, 2°C and 3°C above preindustrial temperature has been analysed and compared to the 1981-2010 control climate window (baseline). The 1.5°C and 2°C warming scenarios are explicitly considered in the Paris Agreement, while a 3°C global warming is a scenario that could be expected by the end of the 21st century if adequate mitigation strategies are not taken.

First, we performed future projections without socio-economic developments to show the effect of climate change only. Next, an integrated assessment is performed including future changes in land use, water demand and population. This allows us to disentangle the effects of climate and socio-economic changes.

In general, the climate projections reveal a typically North-South pattern across Europe for water availability. Overall, Southern European countries are projected to face decreasing water availability, particularly Spain, Portugal, Greece, Cyprus, Malta, Italy and Turkey. Central and Northern European countries show an increasing annual water availability.

Current pressures on water resources are exacerbated in Southern Europe

To demonstrate the ratio between water demand and consumption versus total water availability, we use the Water Exploitation Index Plus (WEI+) (consumption ratio) as an indicator for water scarcity. The WEI+ is defined as the total water net consumption divided by the freshwater resources of a region, including upstream inflowing water. WEI+ values have a range between 0 and 1. Different gradations of water scarcity are determined. Values below 0.1 denote "low water scarcity", values between 0.1 and 0.2 denote "moderate water scarcity", "water scarcity" when this ratio is larger than 0.2, and "severe water scarcity" if the ratio exceeds the 0.4 threshold (Faergemann, 2012).

Results show an intensification and a longer duration of water scarcity in the EU under global warming, specifically in the Mediterranean countries. To demonstrate this, the change in water scarcity days (WEI+ > 0.2) relative to the current climate is presented in Figure 1 for the three warming levels. Water scarcity is projected to gradually increase in duration from current climate towards the 3ºC warming level in the Mediterranean regions, especially in the Iberian Peninsula. Here, water scarcity can increase up to more than 1 month per year for the 3ºC warming levels compared to current climate. Furthermore, many areas in the Mediterranean regions are projected to have a WEI+ close to 1.0 (not shown here), meaning that all possible (annual renewable) freshwater is being used. In several of these areas, groundwater amounts are depleting.

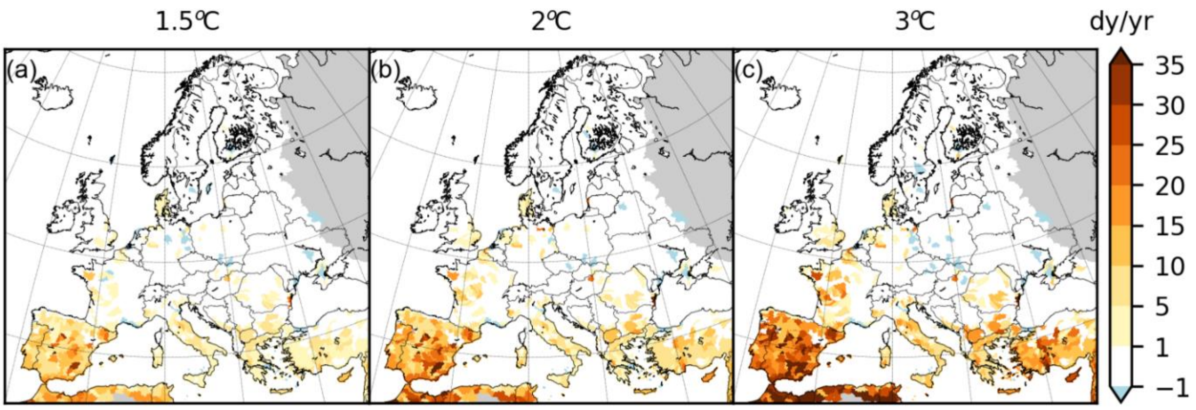

Figure 1. Projected change in water scarcity days (WEI+ > 0.2) in a year compared with present day for a global temperature increase of (a) 1.5°C, (b) 2°C, and (c) 3°C. The results of both the 1.5°C and 2°C warming levels are based on the average of the 11 climate model simulations from both the RCP4.5 and RCP8.5 emission scenarios, while the results of the 3°C warming level are solely based on the 11 simulation of the RCP8.5 emission scenario.

Number of people exposed to water scarcity

An example of putting water scarcity into a societal perspective is to estimate how many people and economic activities are exposed to different gradations of water scarcity. Averages of monthly WEI+ values are calculated for current climate (1981-2010) and for the 30-yr warming periods centred on the year global mean temperature exceeds 1.5°C, 2°C and 3°C for both the RCP4.5 and RCP8.5 emission scenarios. In the case of the simulations without socio-economic developments the results are overlaid with the population and Gross Added Value (GVA) of 2010. The results of the simulations with socio-economic developments are overlaid with the population and GVA of 2050. As a 3°C scenario is not realistic in 2050, only the 1.5°C and 2°C warming period are considered within the simulations with socio-economic developments. Here, in Figure 2, we show the ensemble mean of the 'static' simulations that shows the effect of climate change only.

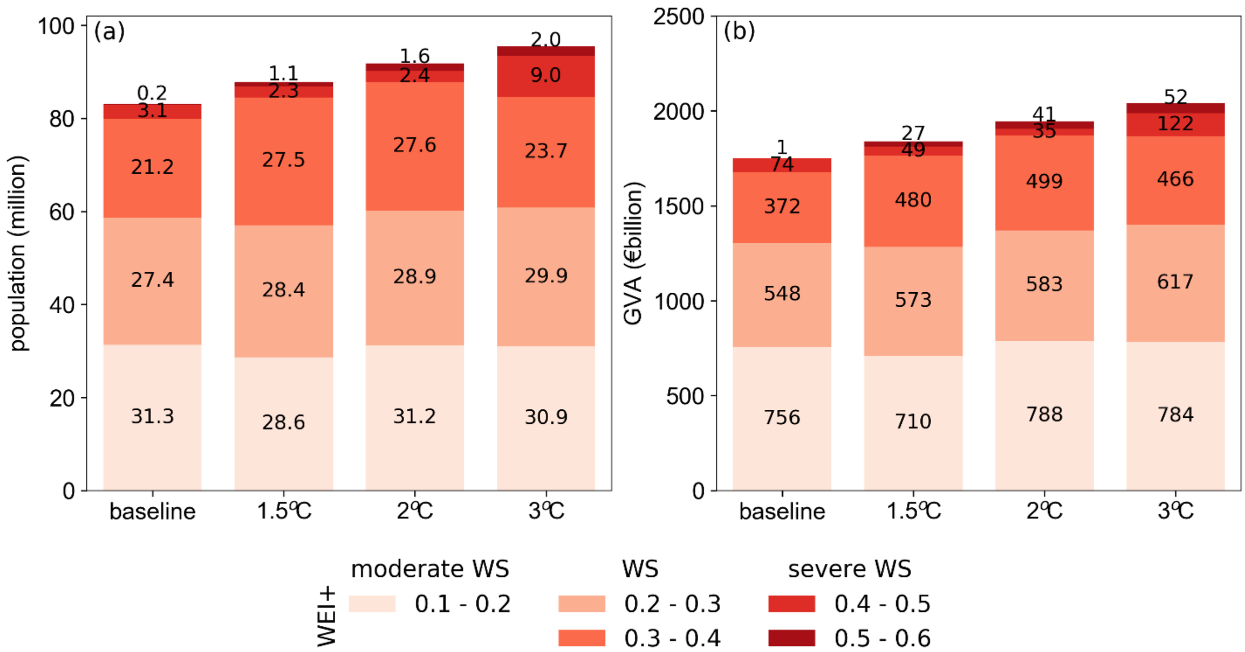

Figure 2. Projected number of (a) people living and (b) economic activity exposed to different gradations of water scarcity (WS) in the EU+UK solely due to climate change for the baseline and under the different warming levels.

Our projections show that in the EU climate mitigation can considerably reduce the number of people and economic activity exposed to severe water scarcity (WEI+ > 0.4), which is in accordance with stress or even clearly unsustainable use of water resources. In the EU+UK, around 51.9 million people and 995 €billion economic activity are at present exposed to water scarcity (WEI+ larger then 0.2), and 3.3 million people and 75 €billion economic activity to severe water scarcity. Even if we manage to 'pursue efforts' to 1.5°C global warming the people and economic activity exposed to water scarcity could still increase with 7.4 million and 134 €billion compared with present climate, but the number of people and economic activity exposed to severe water scarcity, although facing intensified and longer duration of severe water scarcity, remain constant. If not, with unmitigated climate change (3°C), an additional 7.7 million people and 99 €billion economic activity are projected to be exposed to severe water scarcity.

When demographic changes are taken into account, in general the additional number of people exposed to water scarcity is increasing due to population growth in some countries (such as France), but decreasing in other countries due to a projected population decline in countries which are also exposed to severe water scarcity (such as Greece). The projections of the economic activity have a major effect in amplifying the water scarcity in the EU as the economic activity is growing in all EU countries. In general, the number of economic activity exposure can increase to two-fold compared with static economic activity.

If water demand stays at current usage levels and without significant water saving efforts, the warming climate and reduced precipitation in the Mediterranean will cause extreme increases in water scarcity. The people already exposed to water scarcity in current climate will encounter much more intense water scarcity. In addition, many people are projected to be exposed to severe water scarcity in an unmitigated climate.

Adaptation

The severity of impacts under the 1.5°C, 2°C and 3°C warming levels suggests that various adaptation mechanisms will be needed to lessen the effects of climate change on European water resources, in particular in the Mediterranean region. A number of planned adaptation strategies could be targeted at irrigation practices to lower pressures on water resources, e.g. increase irrigation efficiency. Several irrigation efficiency increase efforts are planned within the Water Framework Directive (WFD) Programs of Measures. Water pricing for irrigation water – groundwater, surface water, or re-use of treated waste water, as well as pricing for industrial water and public water, could create incentives for users to consider water savings. Irrigation efficiency could be increased by changing irrigation methods (e.g., from sprinkling to drip irrigation), but this is likely to only be feasible when irrigation water has a price. Furthermore, deficit irrigation strategies may lead to substantial water savings, with only limited reductions in crop yields. More efficient cooling technologies could lead to a reduction in water use for producing energy. In addition, shifts from conventional energy production (coal) to renewable energy production could reduce cooling water demand and net water consumption (Magagna et al., 2019). Changing national or regional water allocation regulations could alleviate water scarcity episodes. In more extreme cases, one might consider stimulating a change to crops that have a smaller (irrigation) water requirement, and critically evaluate subsidising crops in water scarce areas.

1. Introduction

Growing human water demands, due to projected population, socio-economic and climate, change pressures on our water supplies in many regions of the world (Wada et al., 2013; Schewe et al., 2014). Moreover, it is expected that water scarcity is increasing in the coming decades (Gossling and Arnell, 2013). As water is a primary need for all (Vanham, 2016), access to clean water is one of the key factors of the Sustainable Development Goals (SDGs) as agreed by the United Nations in 2015 (UN-GA, 2015).

In view of ongoing global warming other international commitment have also been made to reduce greenhouse gas emissions and to find strategies for climate change adaptation and disaster risk reduction such as the United Nations' Paris Agreement (UNFCC, 2015) and the Sendai Framework for Disaster Risk Reduction 2015 -2030 (UNISDR, 2015). The United Nations' Paris Agreement includes the aim of limiting global warming well below 2°C and pursuing efforts to limit to only 1.5°C above pre-industrial levels.

The protection of European freshwaters has been the subject of several EU legislation, as the Water Framework Directive (WFD) and its specific Directives. Managing and coping with the extremes of water – floods and droughts – are covered under the Floods Directive (FD) and EU Action on water scarcity and droughts.

The understanding of future water scarcity is essential to inform and support climate policy makers for mitigation and adaptation strategies. Water use modules have been already embedded into a number of large-scale hydrological models to investigate water availability on catchment (Bisselink et al., 2018a), European (Aus van der Beek et al., 2010; Bisselink et al., 2018b; Flörke et al., 2012) and global scale (Flörke et al., 2013). However, there is still need to better assess future water consumption related to water scarcity (Wada et al., 2013).

Therefore, in this study, an integrated assessment is performed considering both socio-economic scenarios and climate change scenarios in relation to water scarcity in Europe under global warming.

2. Methodology

The results of this study are obtained using JRC's LISFLOOD water resources model (De Roo et al., 2000; Van der Knijff et al., 2010). Driven by climate projections, LISFLOOD calculates a complete water balance at a daily timestep and every grid cell, here 5x5 km. Freshwater resources are determined under global warming levels (GWLs) of 1.5°C, 2°C and 3°C above preindustrial temperature and the results are compared with those under the baseline (1981-2010) climate. The Water Exploitation Index Plus (WEI+) indicator is used to estimate the intensity, duration and the socio-economic impacts of water scarcity on population and Gross Value Added (GVA). The WEI+ is implemented by the European Environmental Agency (EEA) for identifying water scarcity and regularly updated with data from the EEA member countries in the framework of the State of environmental (SoE) data flows (ETC/ICM, 2016).

The WEI+ is defined as the ratio of the total water net consumption divided by the available freshwater resources in a region, including upstream inflowing water. The total water net consumption is the difference between the water abstraction and the return flow. Water abstractions in LISFLOOD consist of five components from which the irrigation water demand is estimated dynamically within the model as it is driven by climate conditions. The other four sectorial components are used as input data. These are (manufacturing) industrial water demand, water demand for energy and cooling, livestock water demand and domestic water demand. In general, water use estimated for these four sectors are derived from mainly country-level data (EUROSTAT, AQUASTAT) with different modelling and downscaling techniques. Output of the LUISA platform (see Annex A1.2) is used for the spatial downscaling of both present and future water use trends to ensure consistency between land use, population and water demand. Improved water efficiency, based on historical trends, is only taken into account for the industrial water demand. The WEI+ includes return flow, resulting from drained irrigation water, (warmed up) cooling water returned to the river, and (treated) wastewater returned to surface waters. Per sector, water consumption factors are used and applied to split water abstraction into net water consumption and return flow (Bisselink at al., 2018).

Water abstractions take place at regional level, and also the WEI+ is therefore calculated at this regional level at a monthly timescale to avoid averaging skewed results. However, in this report the results are converted to a daily scale.

WEI+ values have a range between 0 and 1. For distinguish water scarcity gradations across Europe, we used the water scarcity values as applied by the EEA Values between 0-0.1 denote "low water scarcity", "moderate water scarcity" if the ratio lies in the range 0.1-0.2, "water scarcity" when this ratio is in larger than 0.2, and "severe water scarcity" if the ratio exceeds the 0.4 threshold (Faergemann, 2012).

First, we performed future projections without socio-economic developments to show the effect of climate change only. Next, an integrated assessment is performed including future changes in land use, water demand and population. This allows us to disentangle the effects of climate and socio-economic changes. More details on the methodology can be found in Annex 1.

3. Results

In this chapter, we first evaluate the projected changes in water availability (section 3.1) and how these are reflected in terms of water scarcity (section 3.2). In section 3.3, we put the future projections of water scarcity into a societal perspective by estimating how many people are living in water scarcity areas (section 3.3.1) and how much GVA is exposed to water scarcity (section 3.3.2).

3.1 Change in average water availability

In Figure 1 the projected change in water availability, expressed as the median streamflow (50th percentile, Q50), under the 1.5ºC, 2ºC and 3ºC GWLs is presented. Southern European countries are projected to face a progressively decrease in water availability, particularly Spain, Portugal, Greece, Cyprus, Malta, Italy and Turkey. Central and Northern European countries show an increase in the average annual water availability.

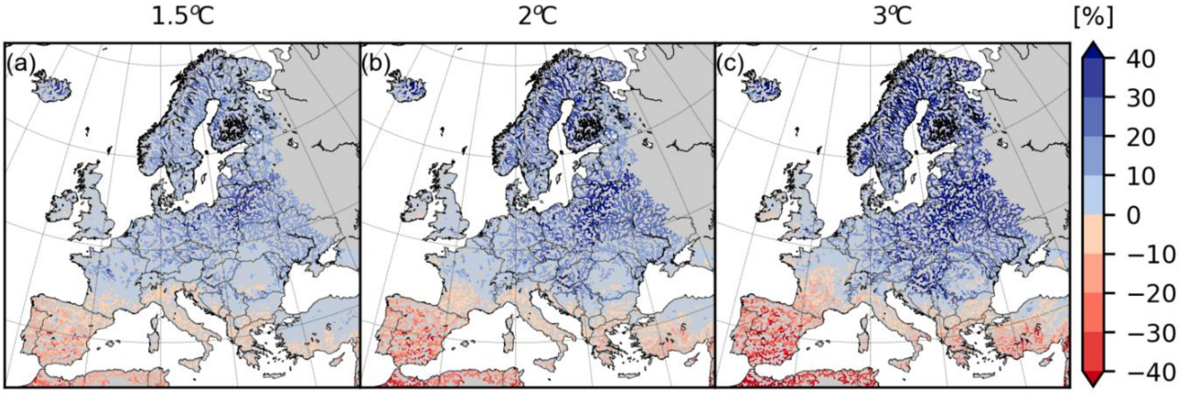

Figure 1. Projected change in average Q50 (median streamflow) compared with the baseline (1981-2010) for a global temperature increase of (a) 1.5ºC, (b) 2ºC, and (c) 3ºC.

3.2 Present and future water scarcity

In present climate, southern regions of Europe already face water stress conditions, with the annual average WEI+ varying between 0.1-0.3 (Figure 2a) in the Mediterranean region[1]. During up to 4 months per year the WEI+ value is higher than 0.2 in the most southern parts of Europe (Figure 2b). The highest average WEI+ values, up to 0.5, are found in Spain. These regions presently experience water stress up to 6 months a year. During summer WEI+ can be close to 1.0, meaning that all possible water is being used, and often also a substantial amount of non-renewable groundwater.

Under the 1.5ºC GWL, the WEI+ values are increasing. In Figure 3, we consider the spatial pattern of change in average WEI+ for the GWLs relative to the baseline. The largest increases take place in the Mediterranean region.

For the 2ºC and even more pronounced for the 3ºC GWL, the WEI+ values are exacerbating in already existing water scarce areas and moreover new water scarce areas are created in countries further north like Germany, Bulgaria, Romania and France.

[1] Note that environmental flow is taken into account in the LISFLOOD model, but is not reflected in the commonly used definition of WEI+. LISFLOOD uses an environmental flow threshold equal to Q10. Thus, if local discharge falls below the 10th percentile Q, further water abstractions from that location are not allowed, and the model flags those amounts. The WEI+ reflects the real net water consumption versus total water availability, so not putting aside an amount of environmental flow not part of this total availability.

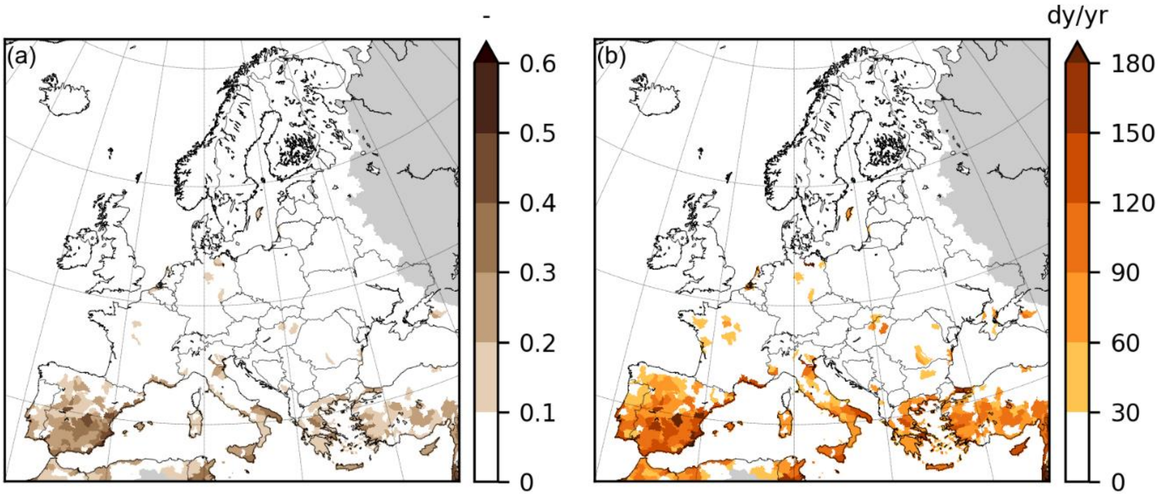

Figure 2. (a) Estimated average WEI+ and (b) the number of days per year in areas with a WEI+ exceeding 0.2 for the baseline scenario (1981-2010).

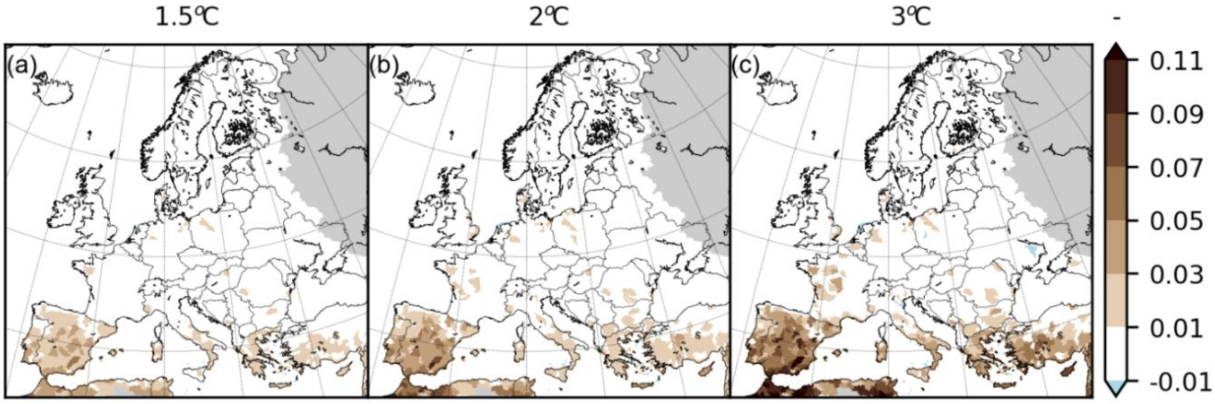

Figure 3. Projected change in average WEI+ compared with the baseline (Figure 2a) for a global temperature increase of (a) 1.5°C, (b) 2°C, and (c) 3°C.

Apart from an intensification of water scarcity under global warming, the duration of the water scarcity period in a year is projected to increase as well. In Figure 4, the change in water scarcity days relative to the baseline is presented for the three GWLs. Water scarcity is projected to gradually increase in duration from present climate towards the 3°C warming levels in the Mediterranean regions, especially in the Iberian Peninsula. Here, the number of water scarcity days can increase up to more than 1 month per year for the 3°C warming levels compared to the present day climate baseline.

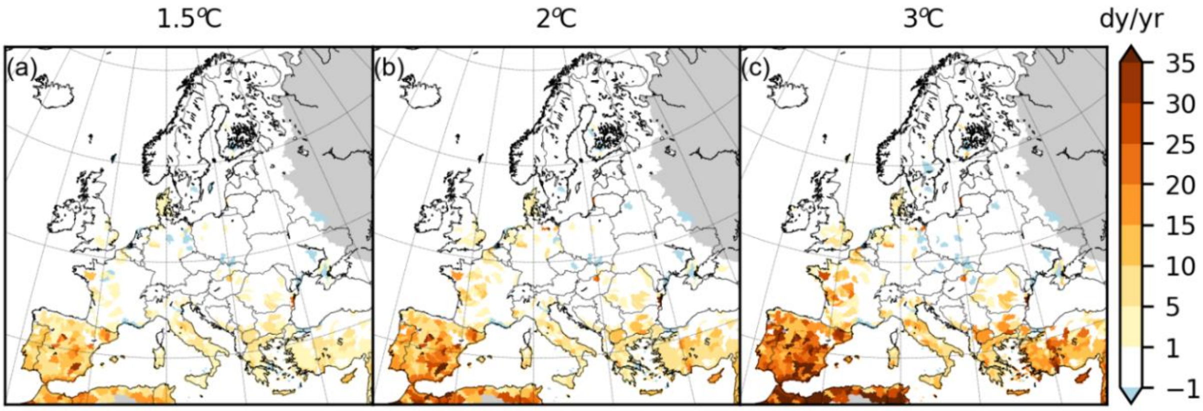

Figure 4. Projected change in water scarcity days (WEI+ > 0.2) in a year compared with the baseline (Figure 2b) for a global temperature increase of (a) 1.5°C, (b) 2°C, and (c) 3°C.

3.3 Socio-economic impacts of future water scarcity

Section 3.3.1 describes the amount population affected by different gradations of water stress. Section 3.3.2 describes the amount of GVA exposed to different gradations of water stress. We present one series of analysis of the climate impact under un-changed land use, population, and water demand changes. Another series of analysis shows the simulations including the effect of climate change with socio-economic developments, so including future changes in land use, water demand and population.

3.3.1 Population

In this section, we aim to put the water scarcity projections into a societal perspective by estimating how many people will be living in areas with different gradations of water scarcity. The results from Figure 5 are based on simulations including the effect of climate change but without socio-economic developments, while in Figure 6 and integrated assessment is performed including future changes in land use, water demand and population. This allows us to disentangle the effects of climate and socio-economic changes. The 'static' simulated water scarce areas are overlaid with the population of the year 2010 and the 'dynamic' simulations are overlaid with the population of 2050. As a 3°C scenario is not realistic in 2050, only the 1.5°C and 2°C warming period are considered within the simulations including socio-economic developments.

In the present climate, 51.9 million people in the EU+UK are living under water scarcity (WEI+ > 0.2) , which is 10.5% of the total population. The most people exposed to water scarcity are living in the Mediterranean region (48.1 million) from which almost half are in Spain (22.4 million; Annex 2). The other exposed people are living in the Atlantic region (3.6 million; France). In the Continental region very few people are living under water scarcity and in the Boreal region people are not exposed to water scarcity, but solely to low (WEI+ 0-0.1) or moderate water scarcity (WEI+ 0.1-0.2).

Under global warming levels, the number of people living under water scarcity in the EU+UK is gradually increasing up to 59.3 million when limiting global warming to 1.5°C. This is an increase of 7.4 million as compared to baseline climate.

Under the 2°C GWL the number of exposed people to water scarcity increases up to 60.5 million people, an increase of 8.6 million as compared to the baseline. Under the 3°C GWL the number of exposed people to water scarcity increases up to 64.6 million people, an increase of 12.7 million compared to the baseline. The number of people living under severe water scarcity is projected to remain more or less constant for present climate, 1.5°C and the 2°C GWLs, but increases with 7.7 million under the 3°C GWL.

In the EU people affected by water scarcity mostly live in Mediterranean countries.

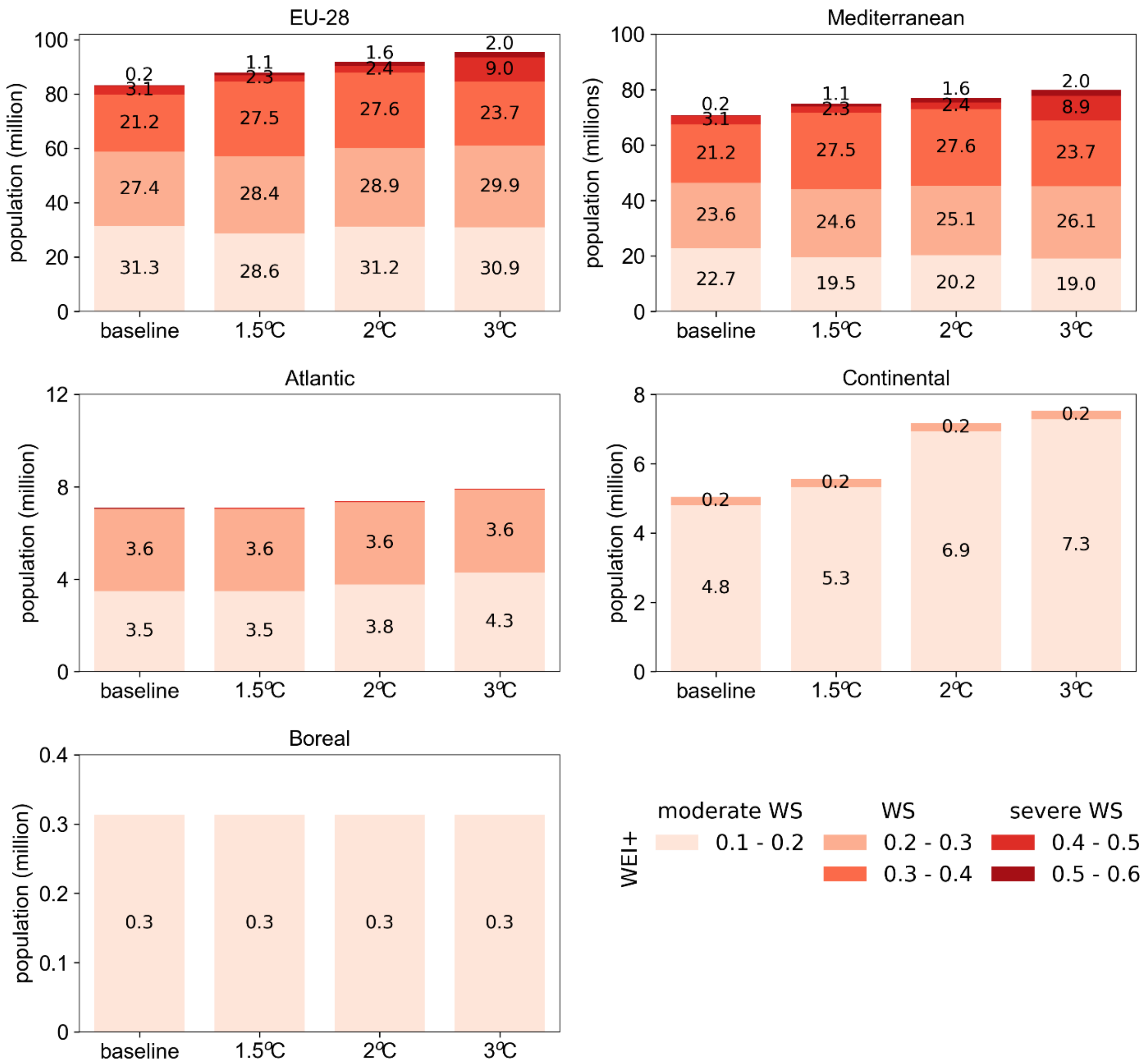

Figure 5. Projected number of people living in different gradations of water scarcity (WS) solely due to climate change for the baseline and under the different warming levels[2].

For the Atlantic countries, the number of people living in water scarce areas remain constant under the GWLs compared with present climate. In both the Atlantic and Continental countries we do project a gradual shift of people who live nowadays in low water scarce areas to moderate water scarce areas under the different GWLs.

When we consider also population projections (Figure 6), an additional 0.6 and 0.8 million people are living in water scarce areas under the 1.5°C and 2°C GWLs, respectively.

Due to the projected population growth in France and Italy our estimated number of affected people by water scarcity increases. However, the population living in severe water scarcity is projected to decline under global warming compared to the simulations that do not consider the socio-economic developments. In the countries where the people are the most exposed to severe water scarcity, like Spain and Greece, the population is projected to remain constant or declining, and therefore the amount of people exposed to severe water scarcity is also remaining constant or declining. As indicated in section 3.2 however, the magnitude and duration of the severe water scarcity is projected to increase considerably.

[2] Mediterranean: Portugal, Spain, Italy, Croatia, Greece, Malta and Cyprus. Atlantic: France, Belgium, Netherlands, UK and Ireland. Continental: Germany, Luxembourg, Austria, Czech Republic, Denmark, Poland, Slovakia, Slovenia, Bulgaria, Romania and Hungary. Boreal: Sweden, Finland, Latvia, Estonia and Lithuania

Due to the projected population growth in France, the projected amount of people living in water scarce areas in the Atlantic countries is increasing as well.

Due to the projected population decline in most of the Continental and Boreal countries, the projected amount of people living in moderate water scarce areas is lower than compared to the simulations without socio-economic developments.

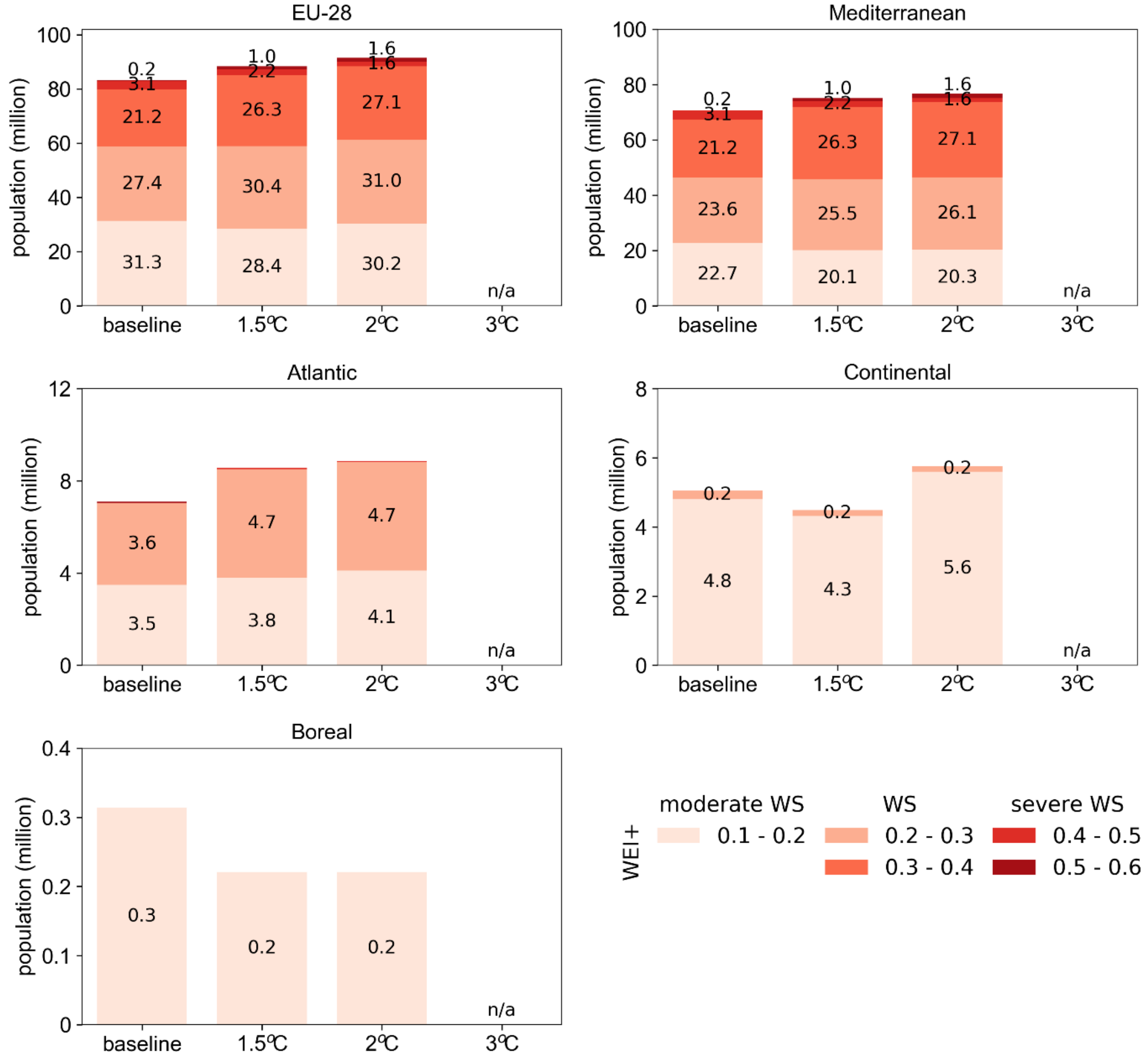

Figure 6. Projected number of people living in different gradations of water scarcity (WS) due to climate change as well as socio-economic developments (population, land use and water demand changes).

3.3.2 Gross Value Added (GVA)

Economic activity of an area is often measured in terms of GVA. Sectors, which rely on water to execute their activities might be affected by water shortages or restrictions under global warming. The industrial sector is responsible for 40% of European water abstractions. Here, the GVA is extracted for the industry sectors that rely on water, including manufacturing industries, mining, construction and services (Bernhard et al., 2019a).

In Figure 7 and 8 we present the GVA values exposed to different gradations of water scarcity. The results from Figure 7 are based on simulations including the effect of climate change but without socio-economic developments, while in Figure 8 an integrated assessment is performed including future changes in land use, water demand and population. The 'static' simulated water scarce areas are overlaid with the GVA of the year 2010 and the 'dynamic' simulations are overlaid with the GVA projection of 2050 for the 1.5°C and 2°C GWLs.

In the present climate, in the EU+UK, 995 €billion of the economic activity is exposed to water scarcity (WEI+ larger then 0.2), which is 9% of the 11108 €billion value of the EU+UK GVA. Of this total number, 882 €billion is exposed in the Mediterranean (32% of the total of 2730 €billion value of the Mediterranean GVA) from which almost half is located in Spain (442 €billion, which is 46% of a total of 965 €billion of the Spanish GVA; Annex 2). The other 113 €billion of the economic activity exposed to water scarcity can be found in the Atlantic regions (France) and to a much lesser extent in the Continental countries (Germany).

The exposure of the economic activity to water scarcity in the EU+UK is gradually increasing up to 1257 €billion under the 3°C GWL, which is an increase of 262 €billion from present day climate. The economic activity exposed to severe water scarcity are more or less constant for present climate, 1.5°C and the 2°C GWLs, but increase with more than 99 €billion under the 3°C GWL.

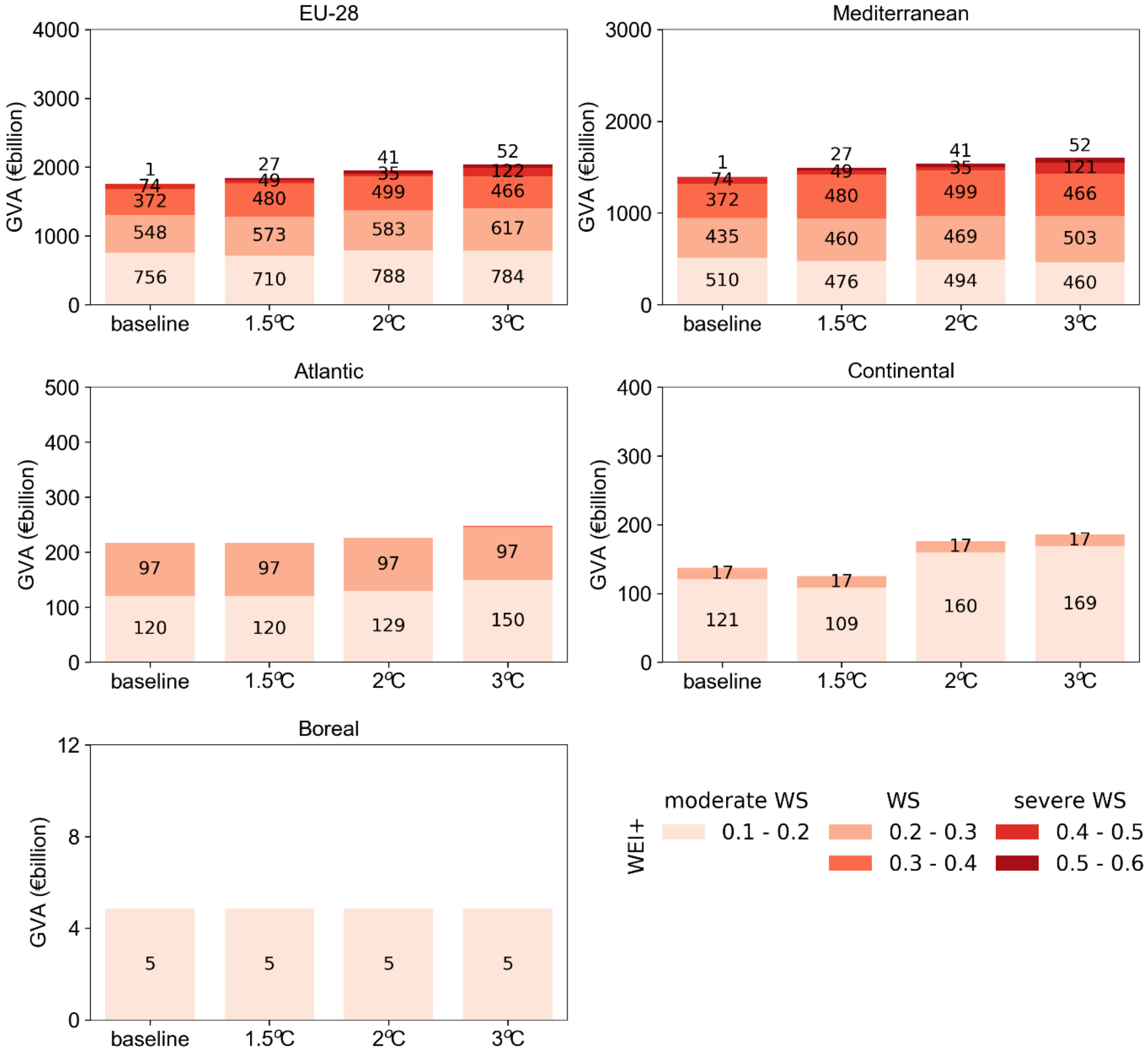

Figure 7. Projected GVA values exposed to different water scarcity (WS) gradations solely due to climate change for the baseline and under the different warming levels.

For the Atlantic countries, the economic activity exposed to water scarcity remain constant under global warming compared with present climate. The most pronounced changes for both the Atlantic and the Continental countries can be found in the gradually increase of exposure of the economic activity to moderate water scarcity. In the Boreal countries no changes in economic activity exposure is observed under global warming compared with present climate.

Considering the GVA projection of 2050 (Figure 8), major changes are observed within in the EU as in all EU-countries economic growth is projected.

In the EU and UK, an additional 703 €billion and 727 €billion economic activity is exposed to water scarcity under the 1.5°C and 2°C GWLs, respectively.

For the Atlantic countries, the economic activity exposed to water scarcity is amplified to more or less twofold due to the economic growth in France compared to the simulations without socio-economic developments. In the Continental and Boreal countries the economic activity exposed to moderate water scarcity are also amplified to more or less twofold due to economic growth.

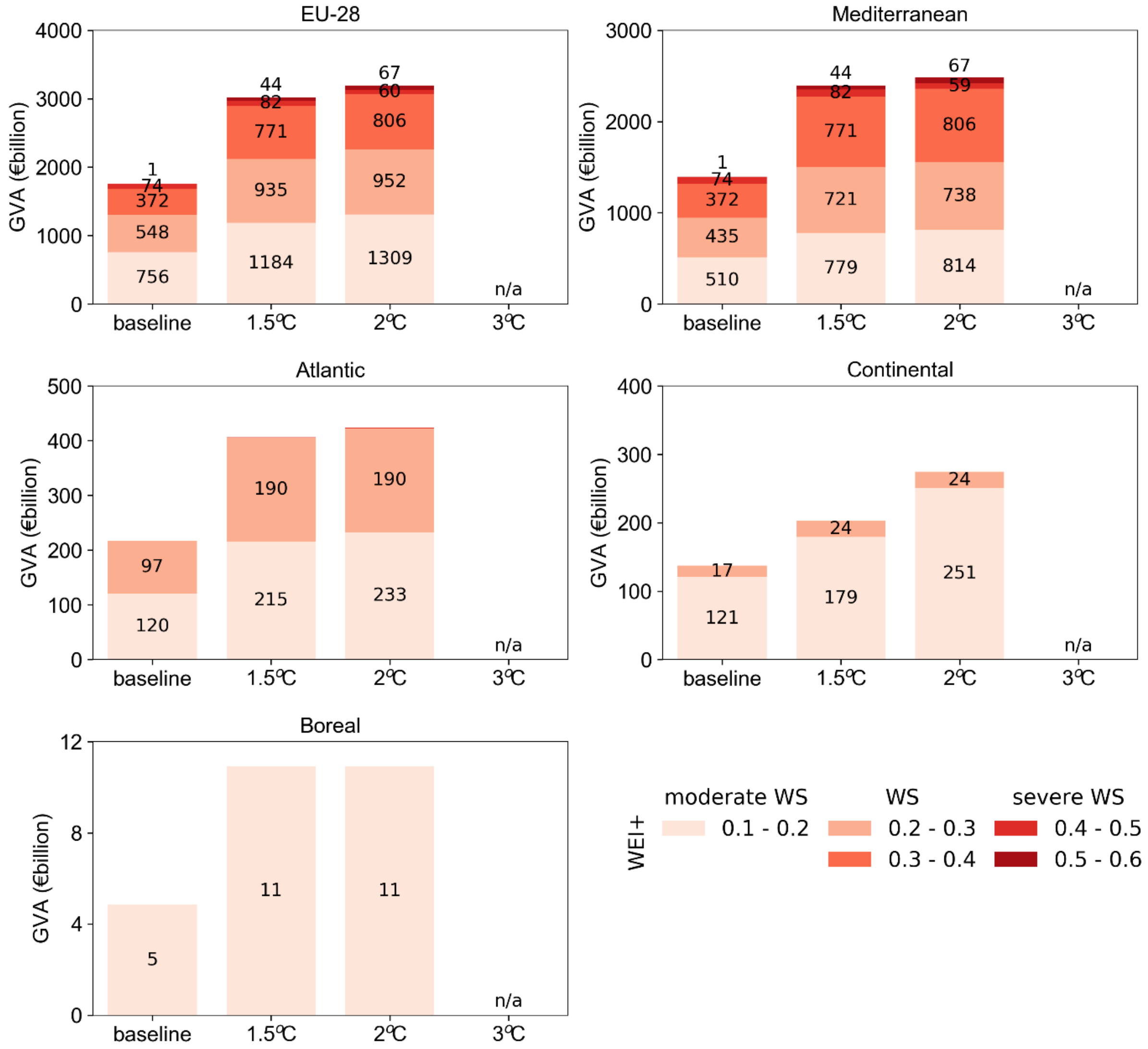

Figure 8. Projected GVA values exposed of different water scarcity (WS) gradations due to climate change as well as socio-economic developments (population, land use and water demand changes).

4. Conclusions

The results presented here are based on 11 climate models which project current and future climate under two Representative Concentration Pathways (RCPs): RCP4.5 and RCP 8.5 emission scenario. A 30-year window around the year that global warming reaches 1.5ºC, 2ºC and 3ºC above preindustrial temperature has been analysed and compared to the 1981-2010 control climate window (baseline). The three GWLs do reflect different levels of mitigation.

In the assessment we show that the impact of climate change on water resources in the EU is an intensification of water scarcity in already water scarce areas, as well as an increase in duration of the water scarcity. This is mainly affecting the Mediterranean countries. However, under 2 and 3°C global warming, we do observe an extension of water scarce areas further north in Central Europe as well.

Our projections show that in the EU climate mitigation can considerably reduce the number of people and economic activity exposed to severe water scarcity (WEI+ > 0.4). In areas with severe water scarcity the use of water resources is often unsustainable, with a noticeable groundwater depletion.

In the EU+UK, around 51.9 million people and 995 €billion economic activity are at present exposed to water scarcity (WEI+ > 0.2) from which 3.3 million people and 75 €billion economic activity to severe water scarcity.

Even if we manage to pursue efforts to keep within a 1.5°C global warming level, the number of people and value of the economic activity exposed to water scarcity could still increase with 7.4 million (+14%) and 134 €billion (+13%) compared with present climate. The number of people and economic activity exposed to severe water scarcity, although facing intensified and longer duration severe water scarcity, is projected to remain almost constant, + 2.4% and +1.3% respectively.

With unmitigated climate change (3°C), an additional 7.7 million people and 99 €billion economic activity relative to 1.5°C GWL are projected to be exposed to severe water scarcity. Limiting warming to 1.5°C reduces the number of people and economic activity exposed to severe water scarcity to 3.4 million and 76 €billion respectively.

In current climate, solely people and economic activity in Spain (3.3 million; 75 €billion) are exposed to severe water scarcity. Without stringent mitigation and adaptation actions, people and economic activity in Greece (3.9 million; 50 €billion) and Malta (0.4 million; 5 €billion) are projected to be exposed to severe water scarcity as well. In other countries around the Mediterranean, an increase in the number of people and economic activity is projected to have water scarcity exposure.

Climate change is the main driver for populations to be exposed to water stress in Southern Europe. Demographic, land use and water demand changes have a minor effect on the people exposed to water scarcity. For example, the increase of number of people exposed to water scarcity in the 1.5°C warming period is +15%, an additional increase of only 1% compared to the static population scenario due to population growth in France. Considering dynamic population, the people exposed to severe water scarcity in the EU is decreasing with 3.4%, mainly due to population decline in Greece.

The projections of the economic activity do have a major effect in amplifying the exposure to water scarcity in the EU. The number of economic activity exposed to water scarcity in the 1.5°C warming period increases by almost two-fold (+84%) compared to present climate from which 71% due to the rapid increase of economic activity in all (Southern European) EU countries. The economic activity exposed to severe water scarcity is increasing with 68% to 126 €billion almost solely due to the increase of the economic activity.

If water demand remains at current usage levels and without significant water saving and/or efficiency efforts, the warming climate and reduced precipitation in the Mediterranean causes extreme increases in water scarcity. The people already exposed to water scarcity in the current climate will encounter much more intense water scarcity under a changing climate. Under an unmitigated climate, many people in the Mediterranean areas are projected to be exposed to severe water scarcity.

The severity of impacts under the 1.5°C, 2°C and 3°C warming levels suggests that various adaptation mechanisms will be needed to lessen the effects of climate change on European water resources, particularly in the Mediterranean region. A number of planned adaptation strategies could be targeted at irrigation practices to lower pressures on water resources, e.g. increase irrigation efficiency. Several irrigation efficiency increase efforts are planned within the WFD Programs of Measures, but first calculations (JRC 2020 in prep) seem to indicate that these measures are likely not sufficient to counter the expected climate effects.

Water pricing for abstracting irrigation water – groundwater, surface water, or re-use of treated waste water, as well as pricing for industrial water, and public water, could create incentives for users to consider water savings, especially in the water scarce regions. Changing the rules for allocation and/or regulations might also be an alternative. Irrigation efficiency could be increased by changing irrigation methods (e.g., from sprinkling to drip irrigation), but this may only be feasible when irrigation water has a price. The investments for the drip irrigation technology need to be recovered by a reduced water bill.

Furthermore, deficit irrigation strategies may lead to substantial water savings with only limited reductions in crop yields. Further research and field experimentations are necessary here.

Other options for water saving might focus on delivering more efficient cooling technologies that lead to a reduction in water use for producing energy. In addition, shifts from conventional energy production (coal, gas) to renewable energy production (wind, solar) could reduce cooling water demand and net water consumption.

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Annexes

Annex 1. Methodology

A1.1 Climate projections

Projections of water scarcity are based on two Representative Concentration Pathways (RCPs): RCP4.5 and RCP8.5. RCP4.5 may be viewed as a moderate-emissions-mitigation-policy scenario and RCP8.5 as a high-end emissions scenario. Statistical and quantitative hazard analyses in this report are performed over 30-year time periods. The reference scenario spans the period 1981-2010. We compare impacts for the baseline with those over 30-year time slices centred on the year that global average temperature is 1.5, 2 and 3°C above preindustrial temperature (Table A1). The 1.5°C and 2°C warming scenarios are explicitly considered in the Paris Agreement, while a 3°C global warming is a scenario that could be expected by the end of the 21st century if adequate mitigation strategies are not taken.

Table A1. Regional climate projections used in the heat and cold impact analysis and corresponding year of exceeding 1.5, 2 and 3°C warming.

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

For each RCP an ensemble of 11 EURO-CORDEX combinations of Global Climate Models (GCM) and Regional Climate Models (RCM) were used (Jacob et al., 2014). Water scarcity conditions at 1.5° and 2°C warming were derived from an ensemble of 22 climate projections (11 RCP4.5 and 11 RCP8.5 members), whereas the ensemble projections for 3°C warming are based on RCP8.5 only, as 10 out of 11 RCP4.5 climate simulations do not reach 3°C warming.

It should be noted that we derived climate at global warming levels from transient climate projections, which may differ from stabilized climate at those warming levels. Studies (e.g., Maule et al., 2017) suggest that the effect of pathway to global warming levels is small compared to the models' variability, expect for strongly not time-invariant variables such as sea level rise.

A1.2 Socio-economic scenarios

We performed the model assessment with static as well as with dynamic socio-economic conditions in Europe. The static approach provides information on how climate change only affect today's societies in Europe at different GWLs. For the static maps, 2010 is the reference year.

The future projections of land use in Europe are derived from the LUISA modelling platform (Jacobs-Crisioni et al., 2017). LUISA translates socio-economic trends and policy scenarios into processes of territorial development. Among other things, LUISA allocates (in space and time) population, economic activities and land use patterns which are constrained by biophysical suitability, policy targets, economic criteria and many other factors. Except from the constraints, LUISA incorporates historical trends, current state and future projections in order to capture the complex interactions between human activities and their determinants. The mechanisms to obtain land-use demands are described in Baranzelli et al. (2014) and Jacobs-Crisioni et al. (2017). Key outputs of the LUISA platform are fine resolution maps (100m) of accessibility, population densities and land-use patterns covering all EU member states and the UK, Serbia, Bosnia Herzegovina and Montenegro until 2050. Corine land use maps are used to cover the rest of Europe. Although LISFLOOD normally operates on a substantially coarser resolution, the details of the LUISA output will remain for a large part due to the use of sub-grid fractions in LISFLOOD as explained in Section A1.3. For a complete description of the LUISA modelling platform and its underlying mechanics we refer to (Batista e Silva et al., 2013; Lavalle et al., 2011).

Water demand in LISFLOOD consist of five components from which the irrigation water demand is estimated dynamically within the model as it is driven by climate conditions. The irrigation water demand with a distinction in simulation methods for crop irrigation and paddy rice irrigation is described in Bisselink et al. (2018).

The other four sectorial components are used as input data. These are (manufacturing) industrial water demand, water demand for energy and cooling, livestock water demand and domestic water demand. Per sector, water consumption factors are used and applied to split water abstraction into net water consumption and return flow (Bisselink at al., 2018).

In general, water use estimated for these four sectors are derived from mainly country-level data (EUROSTAT, AQUASTAT) with different modelling and downscaling techniques as described in Vandecasteele et al. (2014). Output of the JRC LUISA land use projection platform is used for the spatial downscaling of both present and future water use trends to ensure consistency between land use, population and water demand. A brief description of each sectorial component is given below.

Livestock water withdrawals are estimated by combining water requirements from literature with livestock density maps for cattle, pigs, poultry, sheep and goats. The methods are described in detail by Mubareka et al. (2013).

For the energy and cooling demand, national water use statistics are downscaled to the locations of large power thermal power stations registered in the European Pollutant Release and Transfer Register data base (E-PRTR). Subsequently, the temporal trend of energy water use is simulated based on electricity consumption projections from the POLES model (Prospective Outlook on Long-term Energy Systems).

Industrial water demands are based on country-level Figures from national statistics offices for the total water use by manufacturing industries, mining, construction and services. Future industrial water use trends are simulated based on GVA projections for these sub-sectors from the GEM-E3 model to represent industrial activity and an efficiency factor, based on historical trends, to represent improving water efficiency due to technical developments (Bernhard et al. 2019a). Since the GEM-E3 model only provide projections for the EU and UK, industrial water use projections are assumed constant for countries outside the EU.

Water demands for the household sector are derived from a specific household water usage module (Bernhard et al. 2019b) which simulates water use per capita based on socio-economic, demographic and climate variables. This model was based on collected data at NUTS-3 from 2000-2013 for all EU countries and the UK on household water use, water price, income, age distribution and number of dry days per year. Subsequently, regression models were fitted to quantify relationships between water use, water price and the other relevant variables for four European clusters of NUTS-3 regions with similar socio-economic and climate conditions. This household water usage module allows us to estimate present and future domestic water use per capita at NUTS-3 level using socio-economic, demographic and climate projections. The water use per capita are multiplied with population maps from the LUISA platform from 2010 up to 2050 for every 5 years. For the years in between the 5yr-window a linear growth is assumed. Consumptive use for the domestic sector is assumed at 20% (EEA, 2005) meaning that 80% flows back in the hydrological system as waste water.

A1.3 Hydrological simulations and water scarcity indicator

Hydrological simulations have been performed with the JRC' LISFLOOD water resources model. LISFLOOD is a GIS-based spatially-distributed hydrological rainfall-runoff model (De Roo et al., 2000; Van der Knijff et al., 2010; Burek et al., 2013). Most hydrological processes in every grid-cell defined in the modelled domain are reproduced and the produced runoff is routed through the river network.

Although LISFLOOD is a regular grid-based model with a constant spatial grid more detailed sub-grid land use classes are used to simulate the main hydrological processes. The model distinguishes for each grid the fraction open water, urban sealed area, forest area, paddy rice irrigated area, crop irrigation area and other land uses. Specific hydrological processes (evapotranspiration, infiltration etc.) are then calculated in a different way for these land use classes. Moreover, sub-gridded elevation information is used to establish detailed altitude zones which are important for snow accumulation and melting processes, and to correct for surface temperature.

Water demands (public water, livestock water, industrial water, cooling water for the energy sector, and irrigation) are abstracted from surface and/or groundwater resources (depending on the region) when available, taken into account the E-flow threshold in rivers, which is a constant (10^{th} percentile of the natural discharge). Irrigation water demand is embedded in the model as this is dependent on the climate. Using a Penman-Monteith approach, the model estimates the required amount of transpiration by vegetation or crop. If this amount of water is not available from soil moisture above wilting point level, the missing amount is designated as the irrigation water demand.

For the analysis of water scarcity changes under global warming, LISFLOOD was forced with the ensemble of 22 (11 RCP4.5 + 11 RCP8.5) CORDEX climate simulations from 1981 up to 2100. LISFLOOD simulations were performed at 5×5 km^2 resolution grid over the extended European domain, which includes all the EU countries, as well as some neighbouring ones such as Albania, Bosnia – Herzegovina, Iceland, Moldova, Montenegro, the Republic of Macedonia (FYROM), Norway, Serbia, and Switzerland at a daily time step.

In this study, the WEI+ indicator is used to determine water scarcity. The WEI+ is defined here as the total water net consumption divided by the freshwater resources of a region. The freshwater resources taken into account to calculate the WEI+ include locally generated runoff and inflowing surface water from upstream countries, lake and reservoir variable storage, and annual groundwater recharge. The WEI+ is determined at monthly timescale to avoid averaging skewed results. As LISFLOOD includes a water abstraction functionality we use water regions to calculate the WEI+. As we do not know the precise location of the water abstraction for a certain activity, we assume the abstraction may well take place in the regional sub-river basin in which the activity is situated. This sub-basin consist then of several individual model pixels. This prevents artefacts of calculating water scarcity that in reality does not exist. LISFLOOD can simulate with any user-defined water region map. Here, we defined water regions as sub-river basins within a single country. Cross-border abstractions are not assumed. Abstraction thus take place at regional level, and also the WEI+ is then calculated at this regional level. For the socio-economic impacts (population and GVA) of water scarcity the regional values are then aggregated to country scale or even larger (EU+UK).

The WEI+ values are ranging between 0 and 1. A high WEI+ index highlights the regions with a net high consumptive use of water. A threshold value for the WEI above 0.4 is often used to indicate that a region is severely water scarce. A WEI+ larger than 0.2 indicates a water scarce region. A WEI+ in the range 0.1-0.2 is classified as moderate water scarce, and a WEI+ lower than 0.1 is indicating a low water scarce area (Faergemann, 2012).

Annex 2. Extended results

The following sections present the projected number of people (A2.1) or GVA (A2.2) in different gradations of water scarcity for the baseline and GWLs aggregated at country scale.

A2.1 Population

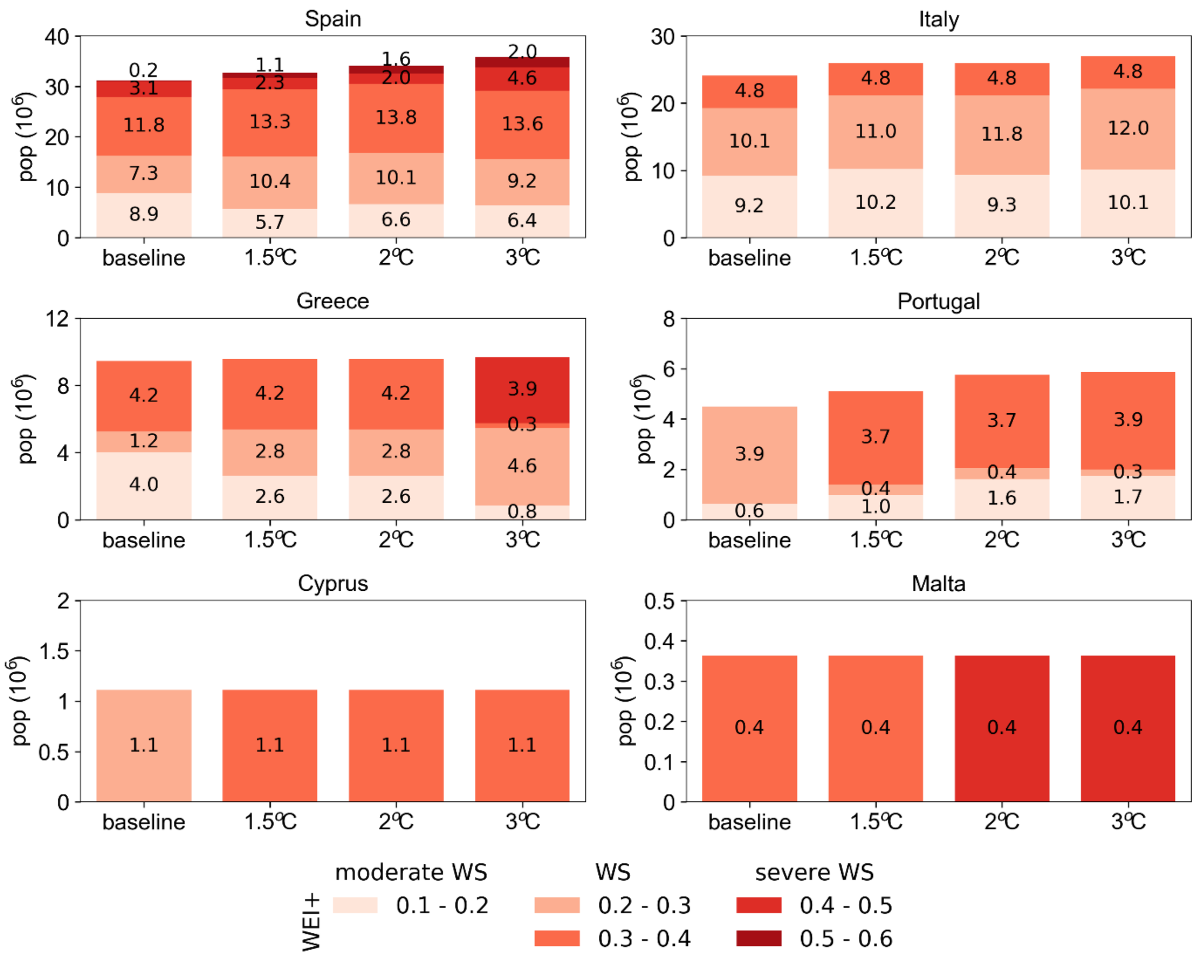

Figure A1. Projected number of people living in different gradations of water scarcity (WS) solely due to climate change for the baseline and under the different warming levels for the Mediterranean countries. Note that in Croatia no changes are observed and therefore Croatia is not presented.

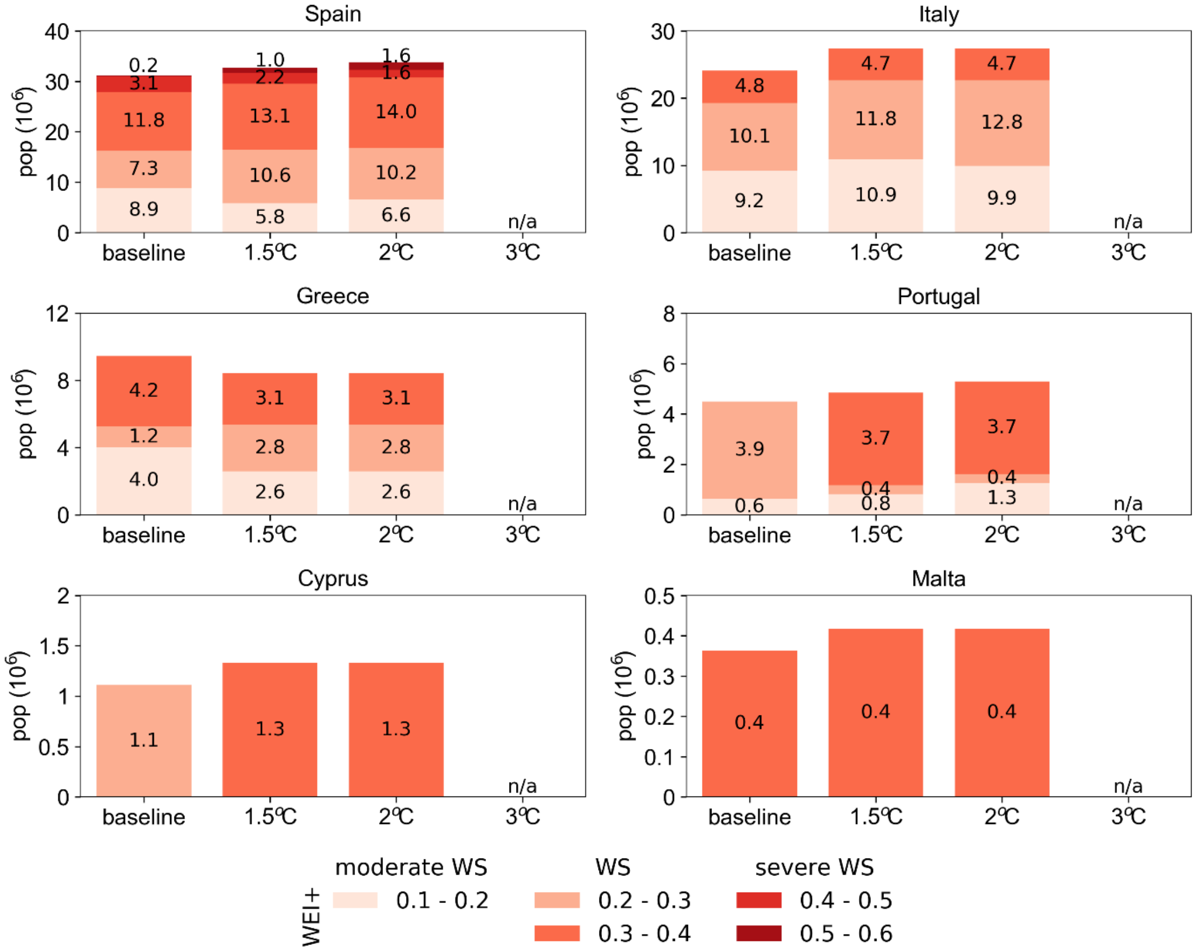

Figure A2. As in Figure A1 but results are from simulations including socio-economic developments.

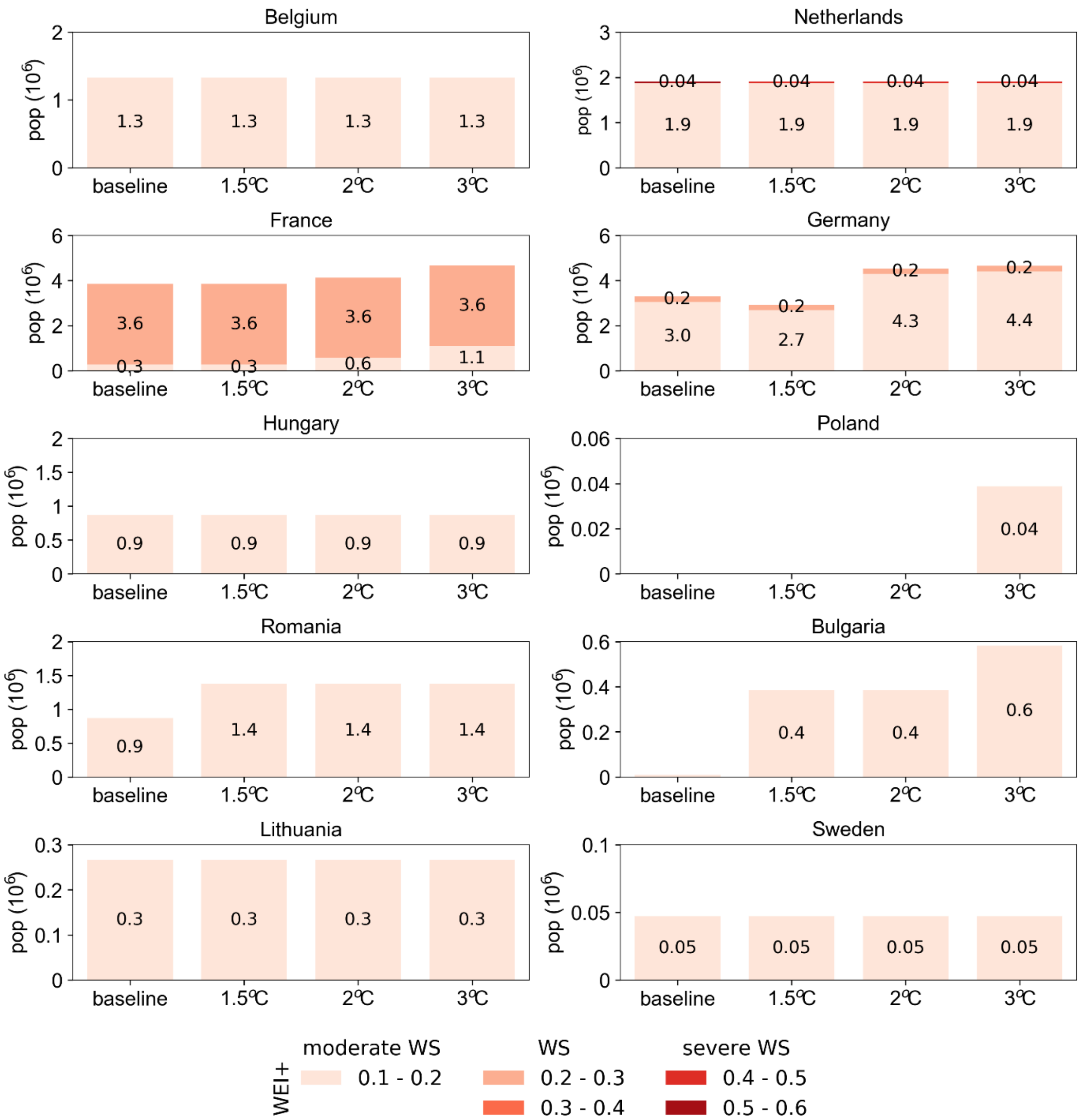

Figure A3. Projected number of people living in different gradations of water scarcity (WS) solely due to climate change for the baseline and under the different warming levels for the Atlantic, Continental and Boreal countries. Note that in Ireland, UK, Finland, Latvia, Estonia, Austria, Slovenia, Czech Republic, Slovakia, Denmark and Luxembourg no or very minimalistic changes are observed and therefore not presented.

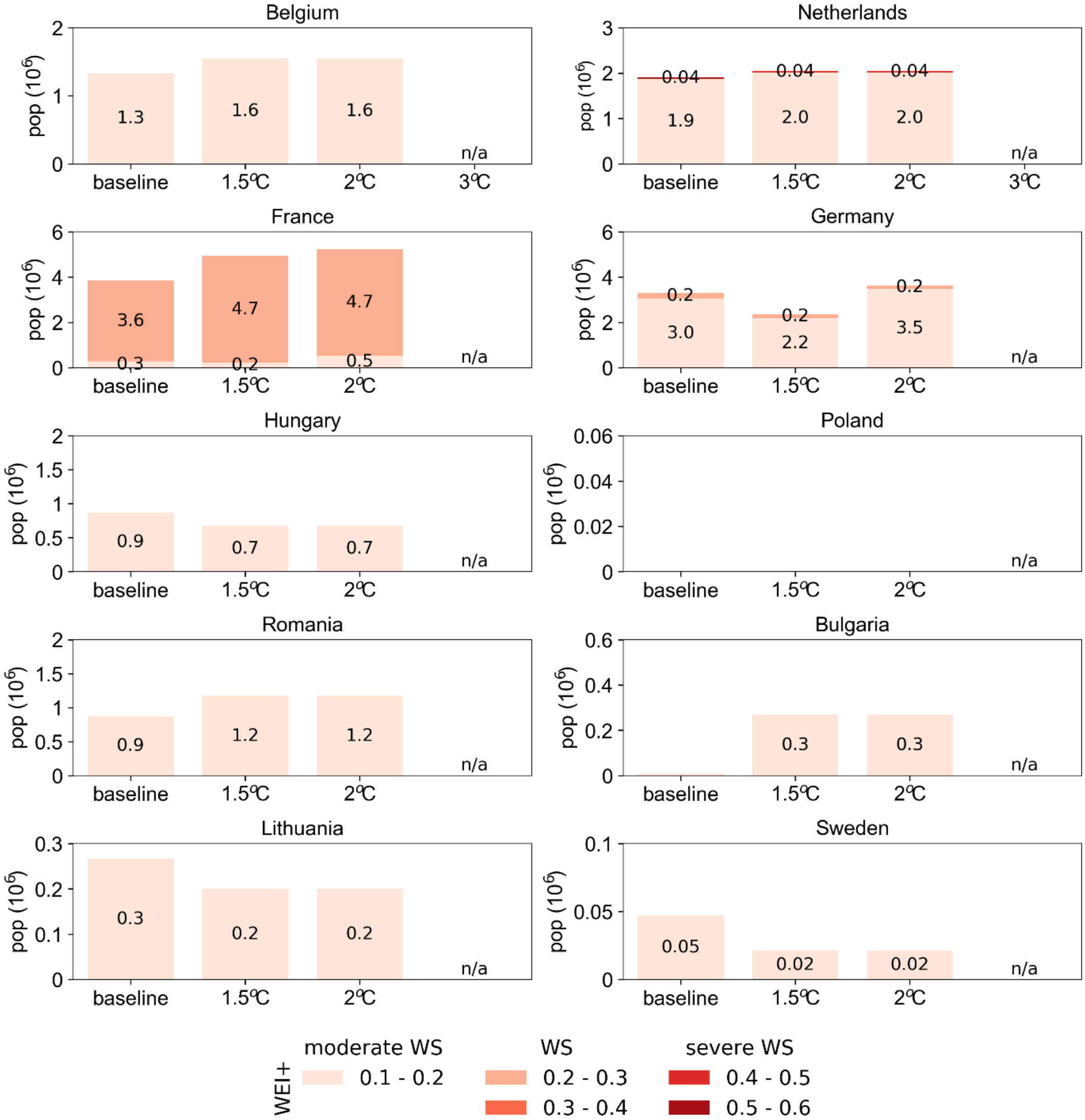

Figure A4. As in Figure A3 but results are from simulations including socio-economic developments.

A2.2 GVA

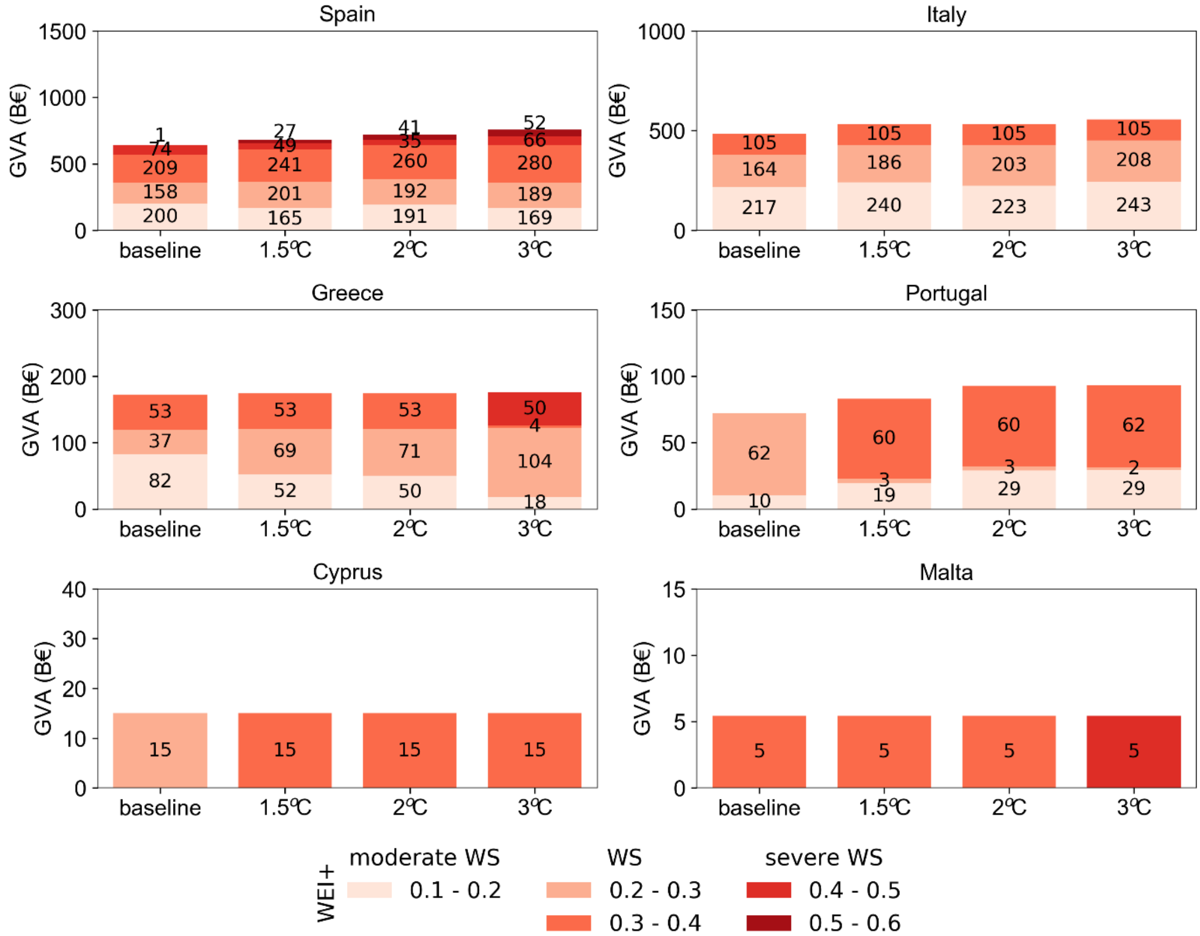

Figure A5. Projected GVA values in different gradations of water scarcity (WS) solely due to climate change for the baseline and under the different warming levels. Note that in Croatia no changes are observed and therefore it is not presented.

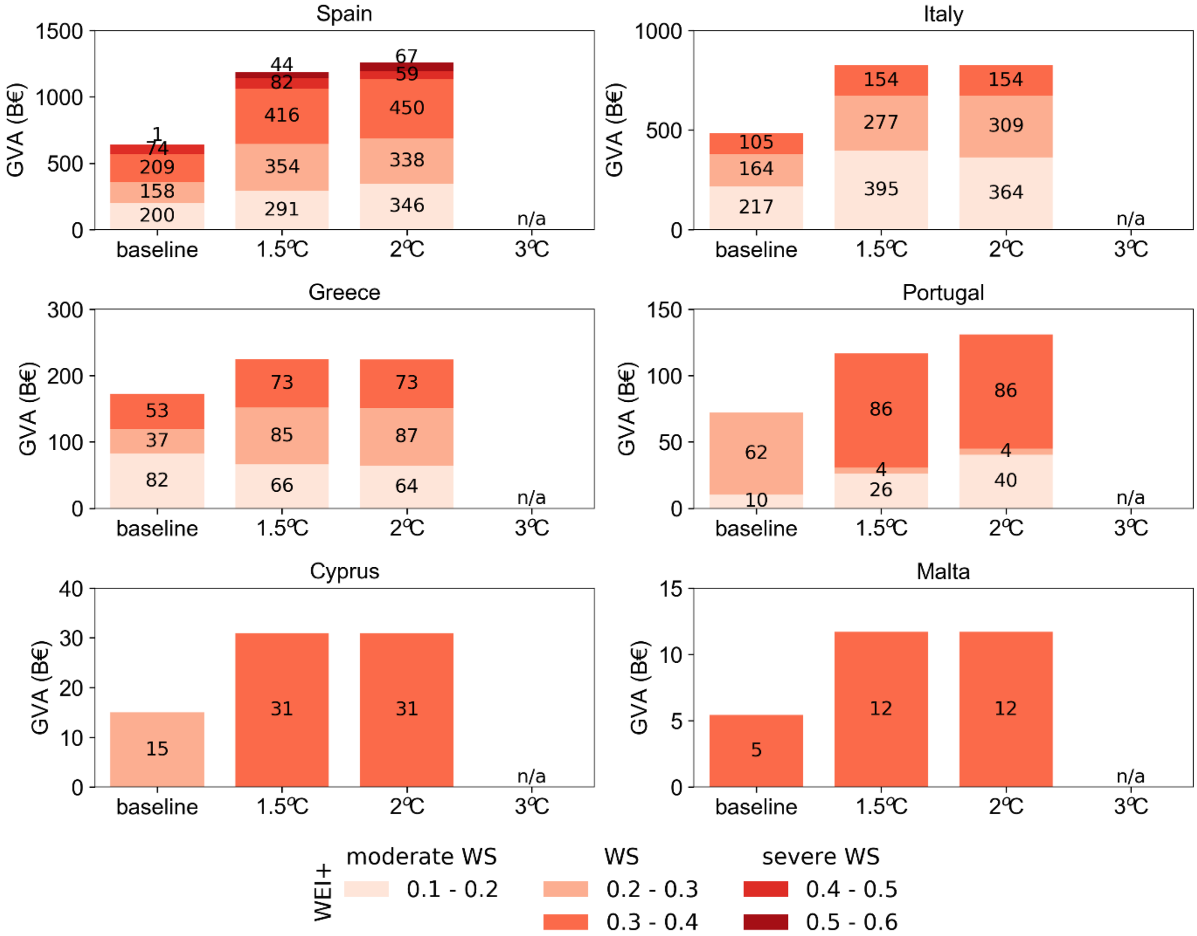

Figure A6. As in Figure *A5* but results are from simulations including socio-economic developments.

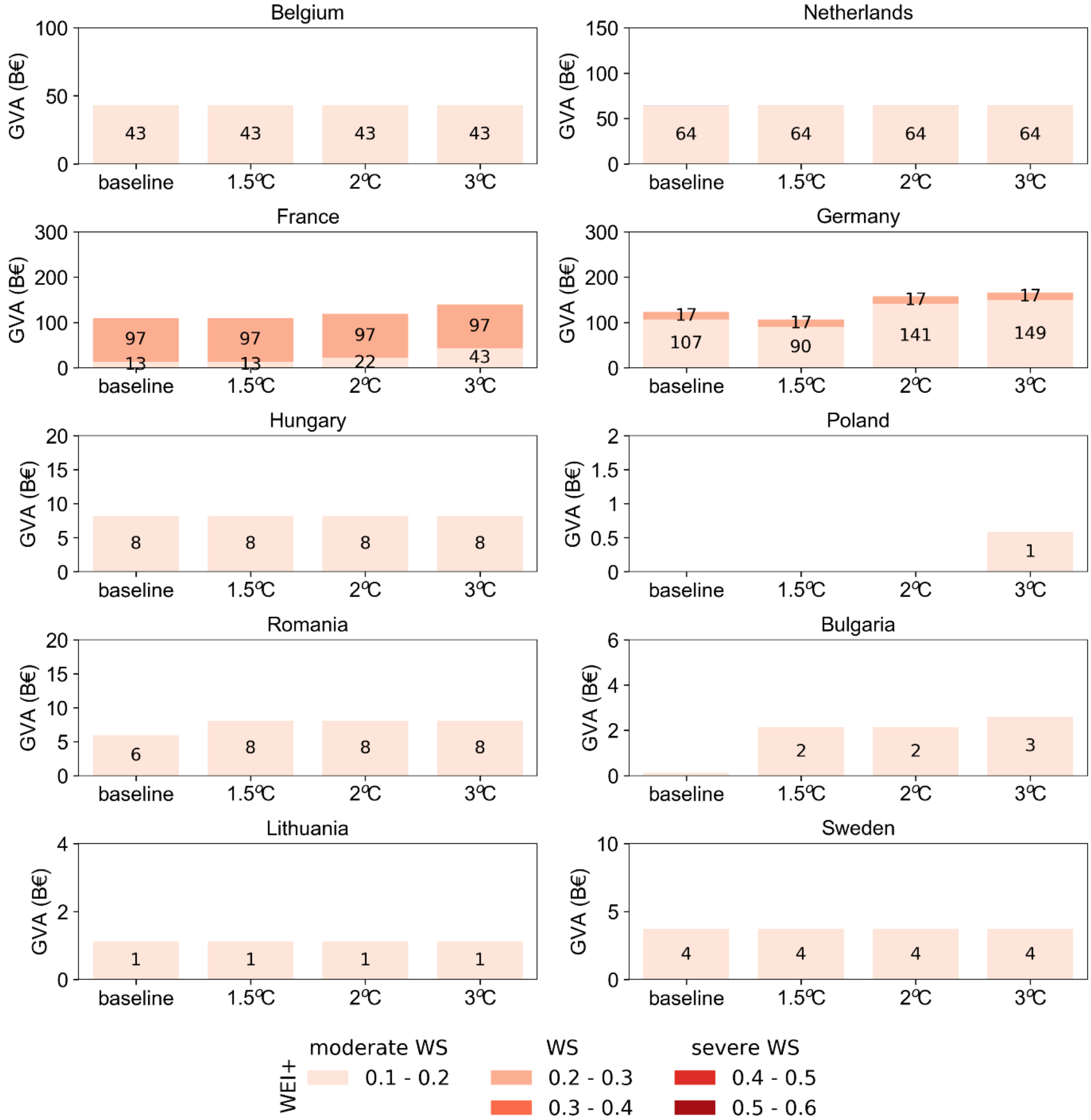

Figure A7. Projected GVA values in different gradations of water scarcity (WS) solely due to climate change for the baseline and under the different warming levels for the Atlantic, Continental and Boreal countries. Note that in Ireland, UK, Finland, Latvia, Estonia, Austria, Slovenia, Czech Republic, Slovakia, Denmark and Luxembourg no or very minimalistic changes are observed and therefore these countries are not presented.

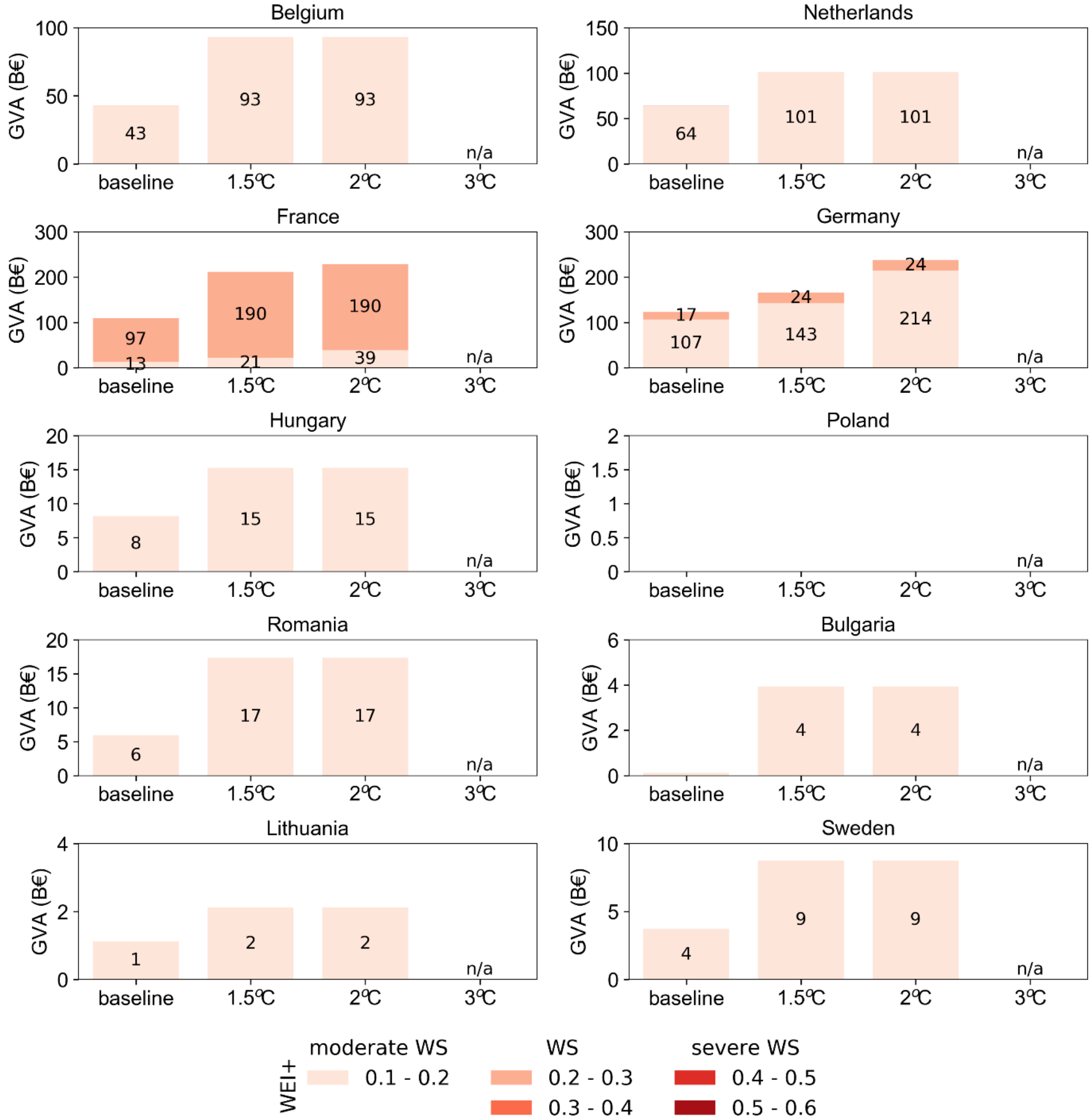

Figure A8. As in Figure A7 but results are from simulations including socio-economic developments.

List of abbreviations

EEA	European Environment Agency
GCM	Global Climate Model
GVA	Gross Value Added
GWL	Global Warming Level
RCP	Representative Concentration Pathway
RCM	Regional Climate Model
SoE	State of Environment
WEI+	Water Exploitation Index +
WFD	Water Framework Directive
WS	Water Scarcity

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