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# Climate change and interconnected risks to sustainable development in the Mediterranean

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**Recent accelerated climate change has exacerbated existing environmental problems in the Mediterranean Basin that are caused by the combination of changes in land use, increasing pollution and declining biodiversity. For five broad and interconnected impact domains (water, ecosystems, food, health and security), current change and future scenarios consistently point to significant and increasing risks during the coming decades. Policies for the sustainable development of Mediterranean countries need to mitigate these risks and consider adaptation options, but currently lack adequate information — particularly for the most vulnerable southern Mediterranean societies, where fewer systematic observations schemes and impact models are based. A dedicated effort to synthesize existing scientific knowledge across disciplines is underway and aims to provide a better understanding of the combined risks posed.**

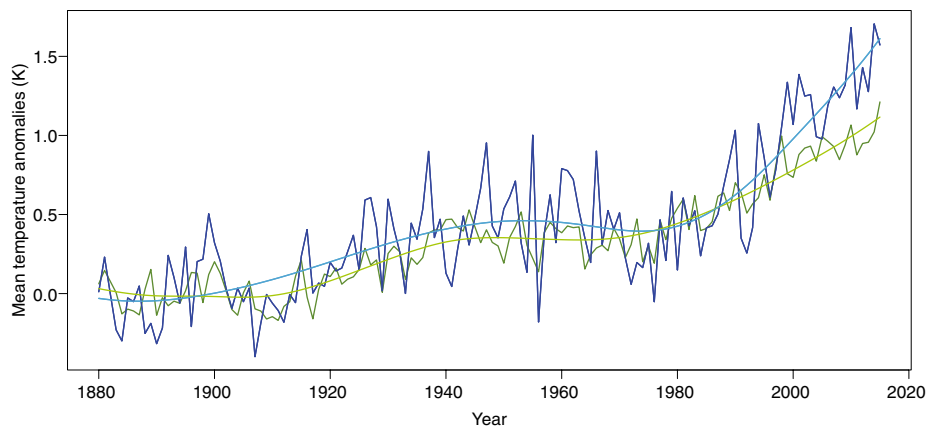
In the Mediterranean Basin, human society and the natural environment have co-evolved over several millennia, experiencing significant climatic variations and laying the ground for diverse and culturally rich communities. The region currently lies in a transition zone between mid-latitude and sub-tropical atmospheric circulation regimes. It is characterized by a complex morphology of mountain chains and strong land-sea contrasts, a dense and growing human population and various environmental pressures. Observed rates of climate change in the Mediterranean Basin exceed global trends for most variables. Basin-wide, annual mean temperatures are now 1.4 °C above late-nineteenth-century levels (Fig. 1), particularly during the summer months. Heat waves now occur more frequently, and the frequency and intensity of droughts have increased since 1950<sup>1–3</sup>. For each of the most recent decades, the surface of the Mediterranean Sea has warmed by around 0.4 °C<sup>4</sup>. During the past two decades, sea level has risen by about 3 cm per decade<sup>5</sup> — comparable to global trends, but in part due to decadal variability related to the North Atlantic Oscillation (NAO). This is a sharp increase when compared to the period 1945–2000 (of  $0.7 \pm 0.2$  mm yr<sup>-1</sup>)<sup>6</sup> and to 1970–2006 when it increased to 1.1 mm yr<sup>-1</sup> (ref. 7). Mediterranean seawater pH currently decreases by 0.018 to 0.028 pH units per decade<sup>8,9</sup>.

Future warming in the Mediterranean region is expected to exceed global rates by 25%, notably with summer warming at a pace 40% larger than the global mean<sup>10</sup>. Even for a ‘Paris-compliant’ global warming of 1.5 °C, a 2.2 °C increase in regional daytime maxima is likely<sup>11</sup>. This increase is expected to be associated with more frequent high-temperature events and heatwaves<sup>12</sup>. In the

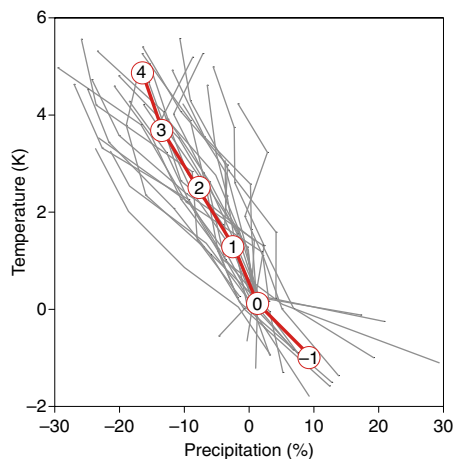
eastern Mediterranean, heatwave return periods may change from once every two years to multiple occurrences per year<sup>13</sup>. A global atmospheric temperature increase of 2 °C will probably be accompanied by a reduction in summer precipitation of around 10–15% in Southern France, Northwestern Spain and the Balkans, and up to 30% in Turkey and Portugal<sup>14</sup>. Scenarios with 2–4 °C temperature increases in the 2080s for Southern Europe would imply widespread decreases in precipitation of up to 30% (especially in spring and summer months) and a switch to a lack of a frost season in the Balkans<sup>15</sup>. For each 1 °C of global warming, mean rainfall will probably decrease by about 4% in much of the region<sup>10</sup> (Fig. 2), particularly in the south, lengthening dry spells by 7% for average global warming<sup>16</sup> of 1.5 °C. Heavy rainfall events are likely to intensify by 10–20%, in all seasons except summer<sup>17,18</sup>.

Global sea-level trends, estimated by the IPCC Fifth Assessment Report (AR5) to be between 52 and 98 cm above present levels by 2100<sup>19</sup>, and between 75 and 190 cm by a semi-empirical model<sup>20</sup> will largely influence the Mediterranean Sea through the transport of water through the Strait of Gibraltar<sup>21</sup>, although the precise contribution is still uncertain due to a lack of knowledge of specific processes. Recent studies of Antarctic ice-sheet dynamics indicate that estimates from process-based models may have to be adjusted upwards by one metre or more for 2100<sup>22</sup>. In addition, the estimated uncertainties in global sea-level projections rely heavily on assumptions concerning the degree of interdependence of the various contributing factors. Model analyses indicate that the difference in the estimated uncertainty range between 20 cm for Representative Concentration Pathway RCP4.5 and 67 cm for RCP8.5 scenarios<sup>23</sup>.

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**Fig. 1 | Historic warming of the atmosphere globally and in the Mediterranean Basin.** Annual mean air temperature anomalies are shown with respect to the period 1880–1899, with the Mediterranean Basin (blue) and the globe (green) presented with (light curves) and without (dark curves) smoothing. Data from <http://berkeleyearth.org/>



**Fig. 2 | Evolution of the Mediterranean regional climate towards warmer and drier conditions.** The trajectory of evolution (red line) describes the ensemble mean as function of global mean temperature change, indicated in the red circles. Results are based on an ensemble of 28 CMIP5 global simulations, each represented by a grey line. All values are anomalies with respect to the corresponding 1971–2000 mean. Data from ref. <sup>10</sup>.

Regional projections of relative sea-level change are more uncertain than global projections because of the reduced skills of global models and how the interaction between the Atlantic Ocean and the Mediterranean Sea is taken into account<sup>24</sup>. For Mediterranean coasts, regional changes in river runoff, the resultant salinity changes and significant land movements in the eastern parts of the basin need to be considered. It has been suggested that in the future Mediterranean sea-level change will be dominated by global sea-level change, but circulation patterns in the Mediterranean could still be modified, thus changing the regional sea-level patterns<sup>25</sup>. This would induce local differences in sea-surface height of up to 10 cm. In Southern Italy, substantial coastal inundation is expected by 2100<sup>26</sup>. Significant shoreline modifications are also expected elsewhere, such as in the Balearic Islands<sup>27</sup>. Globally, CO<sub>2</sub> uptake by the oceans is expected to lead, by 2100, to acidification of 0.15–0.41 pH units below 1870–1899 levels<sup>28</sup> — similar rates must be expected for the Mediterranean<sup>9,29</sup>.

The impacts of climate change on people, infrastructure and ecosystems occur in combination with other trends of environmental change. The population of countries in the Middle East and North

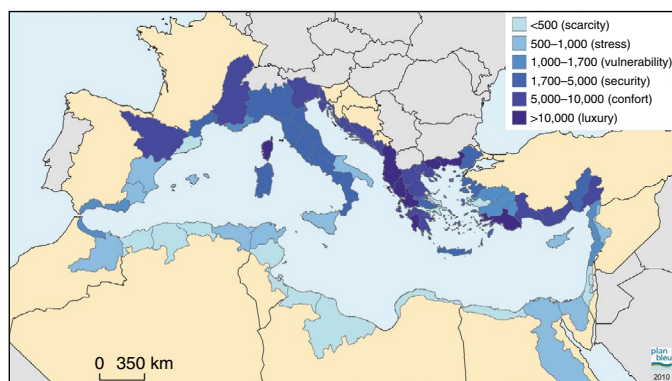
Africa (MENA) has quadrupled between 1960 and 2015, and the degree of urbanization has risen from 35 to 64% during the same period<sup>30</sup>. Agricultural land management is intensifying, particularly through enhanced irrigation — as many southern and eastern land systems seem to have the potential for further increase in yields, agricultural management is likely to change further<sup>31</sup>, with consequences for water resources, biodiversity and landscape functioning. Air and water pollution, despite local improvements from wastewater treatment, increase as a consequence of growing urbanization, transport and other factors. Political conflicts impact the environment dramatically and migration pressure continues, affecting resource-poor economies and reducing their capacity to adapt to environmental change.

### Five interconnected impact domains

The combined risks arising from these forcings can be grouped into five major interconnected domains: water resources, ecosystems, food safety and security, health and human security. Impacts and expected risks differ for each of them. However, the risk posed by their combination demands further attention. Owing to the limitations in resources, the vulnerability to combined risks is unlikely to be a sum of the vulnerability to each separate risk. Instead, their combination may exacerbate the magnitude of the impact or may produce successive, more frequent stress periods, which the least resilient countries will find difficult to cope with.

**Water resources.** Among Mediterranean countries, water resources are unevenly distributed with critical limitations in the southern and eastern part of the basin (Fig. 3). Mediterranean societies will face the double challenge of meeting higher water demands from all sectors with less available freshwater water resources.

Owing to climate change (enhanced evapotranspiration and reduced rainfall) alone, fresh water availability is likely to decrease substantially (by 2–15% for 2 °C of warming), among the largest decreases in the world<sup>32</sup>, with significant increases in the length of meteorological dry spells<sup>16,33</sup> and droughts<sup>34</sup>. River flow will generally be reduced, particularly in the south and the east where water is in critically short supply<sup>15</sup>. The median reduction in runoff almost doubles<sup>16</sup> from about 9% (likely range: 4.5–15.5%) at 1.5 °C to 17% (8–28%) at 2 °C. Water levels in lakes and reservoirs will probably decline. For example, the largest Mediterranean lake, Beyşehir in Turkey, may dry out by the 2040s if its outflow regime is not modified<sup>35</sup>. The seasonality of stream flows is very likely to change, with earlier declines of high flows from snow melt in spring, intensification of low flows in summer and greater and more irregular



**Fig. 3 | Annual natural renewable water resources in the main Mediterranean watersheds.** Resources are expressed as per-capita levels of shortage for human use (in  $\text{m}^3 \text{yr}^{-1}$ ; see legend). Map reproduced with permission from ref. <sup>146</sup>, Plan Bleu.

discharge in winter<sup>36</sup>. In Greece and Turkey per-capita water availability may fall below  $1,000 \text{ m}^3 \text{yr}^{-1}$  (the threshold generally accepted for severe water stress) for the first time in 2030<sup>37</sup>. The critically low current water availabilities per capita in southeastern Spain and the southern shores (Fig. 3) may drop to below  $500 \text{ m}^3 \text{yr}^{-1}$  in future. The importance of meeting environmental flow requirements to ensure the healthy functioning of aquatic ecosystems will require certain amounts of water to be retained in these systems, further limiting availability for human uses<sup>38</sup>.

Other challenges to water availability and quality in coastal areas will probably arise from salt-water intrusion driven by enhanced extraction and sea-level rise, and increasing water pollution on the southern and eastern shores<sup>37</sup>, from new industries, urban sprawl, tourism development, migration and population growth. Recharge of groundwater will be diminished, affecting most of the region. The Northwestern Sahara aquifer system has a renewal rate of only 40% of the withdrawals<sup>39</sup>, indicating high vulnerability of the oasis systems that depend on it.

The general increase in water scarcity as a consequence of climate change is enhanced by the increasing demand for irrigated agriculture to stabilize production and to maintain food security<sup>40,41</sup>. Irrigation demands in the Mediterranean region are projected to increase between 4 and 18% by the end of the century due to climate change alone (for  $2^\circ\text{C}$  and  $5^\circ\text{C}$  warming, respectively). Population growth, and increased demand, may escalate these numbers<sup>42</sup> to between 22 and 74%. Water demand for manufacturing is also projected to increase between 50 and 100% until the 2050s in the Balkans and Southern France<sup>15</sup>. The expected increase in population, particularly in the coastal areas of countries in the eastern and southern Mediterranean, and the increasing urbanization would not only lead to higher water demand, but also to further deterioration of water quality. Satisfying the demands for high-quality drinking water and for increasing irrigation is a complex problem, often involving conflicts between users of groundwater and land owners, or between countries.

The Mediterranean region is regularly affected by flash floods, which are a consequence of short and local heavy rains in small catchments, many of them near the coast in densely populated areas<sup>43</sup>. Flood risk, associated with extreme rainfall events, will increase due to climate change, but also due to non-climatic factors such as increasingly sealed surfaces in urban areas and ill-conceived storm-water management systems. In the Eastern Iberian Peninsula, observations indicate an increase in convective and heavy precipitation concentrated in fewer days, consistent with climate change expected for this part of the basin<sup>44,45</sup>. Projections of flood hazards

thus vary regionally<sup>46</sup>. However, flood risk (also associated with ill-conceived storm water management systems, sealed urban surfaces and major exposure and vulnerability in flood-prone regions) is expected to increase in most areas in the Mediterranean Basin<sup>43,47</sup>. Besides intensity, the timing of floods is also changing; floods are expected to occur up to 14 days earlier per decade in the north of Italy, south of France and eastern Greece, or later (1 day per decade) near the northeastern Adriatic coast, eastern Spain, the south of Italy and Greece<sup>48</sup>.

**Natural and managed ecosystems.** Forests, wetlands, coastal and marine ecosystems in the Mediterranean Basin will be affected by mean and seasonal changes in temperature and precipitation<sup>49</sup>, as well as the changes in extremes. The increase in aridity (mainly due to reduced rainfall, but also to higher temperatures) is probably the main threat to the diversity and survival of Mediterranean land ecosystems<sup>50,51</sup>. Higher fire risk, longer fire seasons and more frequent large, severe fires are also expected as a result of increasing heatwaves in combination with drought and land-use change<sup>52–54</sup>. Falling water levels and reduced water quality are also impacting wildlife in Mediterranean inland wetlands<sup>55</sup> and freshwater ecosystems<sup>32,38,56</sup>. The combination of these impacts with other global change drivers, such as land-use change (urbanization, agricultural abandonment or intensification), biological invasions, pollution and overexploitation, alters the structure and function of organisms, populations, communities and terrestrial ecosystems in the region, often towards drier and less-productive systems<sup>52,57–59</sup>. Interactions between different drivers are complex; however, the net outcome of most changes is likely to be a decrease of the capacity of many ecosystems to supply services at current levels<sup>60,61</sup>.

Climate change is greatly modifying the structure and function of marine and coastal ecosystems. Higher sea temperatures are linked to increased mass mortality events of many different species<sup>62–64</sup>. Impacts of the 2003 heat wave on benthic populations were particularly strong and the geographical scale concerned tens to thousands of kilometres of coastlines<sup>62</sup>. Since 1999 mass mortality events concerning different species have been reported almost every year, although affecting fewer species and more limited in geographic range<sup>63</sup>.

Shifts in the geographic distribution of a great diversity of native species (including fishes, crustaceans and echinoderms) have been linked to warming trends<sup>65–68</sup>. Warm-water species are moving northwards, colonizing and establishing permanent populations in new areas — in some cases within a few years. Meanwhile, in the northern oceanic areas, warming is reducing suitable habitats for cold-water species, causing significant decreases in their abundance and even local extinctions<sup>66,69,70</sup>. The widening of the Suez Canal and the transport of alien species through ballast water from ships worsen the situation. The wider consequences of the modifications to species composition on ecosystem functioning are still uncertain; however, interspecific interactions (competition, for example) are already causing changes in habitat use by former residents<sup>70</sup>.

More than 700 non-indigenous marine plant and animal species have been recorded so far in the Mediterranean<sup>71</sup>, many of them are favoured by the warmer conditions<sup>64,66</sup>. More than 50% of these have entered through the Suez Canal. The eastern Mediterranean is the area displaying the most severe environmental effects from invasive species<sup>72</sup>. During the coming decades, more tropical invasive species are expected to find suitable environmental conditions to colonize the entire Mediterranean, spreading the ecological consequences already observed in some areas<sup>72</sup>.

Ocean acidification is expected to have a significant impact on a wide array of organisms that produce carbonate shells and skeletons<sup>9,29</sup>. The effects encompass biological (such as early-stage survival), as well as ecological (loss in biodiversity, changes in biomass and trophic complexity, for example) processes<sup>73</sup>. Effects of recent



acidification in the Mediterranean Sea have led to a significant decrease in the thickness of coccoliths, calcareous plates constructed by some phytoplankton, between 1993 and 2005<sup>8</sup>. Overall, effects are highly species-dependent. At the community level, modifications in species composition and abundance — from assemblages dominated by calcifying species to non-calcified species such as erect macroalgae — were reported even under moderate decrease in pH<sup>74–76</sup>. In coming decades, synergies between warming and acidification are likely to affect a large number of marine species; including commercial species such as mussels<sup>77</sup>.

These ecological changes on land and in the ocean lead to an overall biodiversity loss. They may also compromise the numerous benefits and services that Mediterranean ecosystems provide, including renewable natural resources (such as food, medicines, timber), environmental services (maintenance of biodiversity, soils and water, regulation of air quality and climate, carbon storage, for example) and social services (such as opportunities for recreational, educational and leisure uses, traditional cultural values)<sup>78,79</sup>.

**Food production and security.** Food production from agriculture and fisheries across the Mediterranean region is changing, due to social, economic and environmental changes<sup>80,81</sup>. Although human population growth and increased affluence in some regions, along with changing diets, will lead to higher demand for food products, crop, fish and livestock yields are projected to decline in many areas due to climatic and other stress factors. In addition to the effects of drought, extreme events such as heat waves, frost or heavy rainfall during critical phenological stages may bring unexpected losses due to crop diseases, yield reductions and increased yield variability<sup>82,83</sup>. Yields for many winter and spring crops are expected to decrease due to climate change, especially in the South. By 2050 yield reductions by 40% for legume production in Egypt, 12% for sunflowers and 14% for tuber crops in southern Europe have been estimated. Warming will also affect olive production by increasing irrigation requirements<sup>84</sup>, the risk of heat stress around flowering and the lack of chilling accumulation (time with cold weather required for blossoming)<sup>85</sup>, and by altering fly infestation risk<sup>86</sup>. Although the impact is not projected to be large for aggregated production, local and regional disparities will emerge<sup>86</sup>. Changes in the phenological cycle towards shorter duration and earlier flowering are projected for grapevines, with associated increases in the exposure to extreme events and water stress<sup>87</sup>. These conditions could also affect grape quality. Anticipated flowering and chilling accumulation are expected to impact yields from fruit trees as well<sup>88</sup>. For vegetables such as tomatoes, reduced water availability will be the main yield-limiting factor<sup>89</sup>, although water-saving strategies to enhance the quality and nutritional aspects while maintaining satisfactory yield levels could be developed<sup>90</sup>. In some crops, yield increases may occur, due to CO<sub>2</sub>-fertilization effects that could increase water-use efficiency and biomass productivity<sup>82</sup>, although the complex interactions among the various factors and current knowledge gaps imply high uncertainties<sup>91</sup>. Furthermore, these yield increases are expected to be combined with decreased quality (for example, lower protein content in cereals)<sup>92</sup>. Pests and diseases, as well as mycotoxins, could also represent a serious threat under unfavourable climate conditions<sup>93</sup>. Sea-level rise, combined with land subsidence, may significantly reduce the area available for agriculture in some areas. The effects of sea-level rise will impose additional constraints on agricultural land, especially in subsiding productive delta regions such as the Nile delta<sup>94</sup>.

Livestock production systems play a central role in climate change and agriculture due to their production, environmental and social functions<sup>95,96</sup>. The Mediterranean region is currently characterized by mixed production systems in the northern regions and in some southern ones, whereas grazing systems dominate the southern regions<sup>97</sup>. The number of agricultural holdings with

grazing livestock is in decline (but associated with an increase in the number of animals per farm)<sup>95</sup>. The abandonment of marginal land threatens the future of these pasture-based systems. A transition to mixed crop–livestock systems could help to reduce the costs of climate and increase resilience to climate extremes in the Middle East and North Africa<sup>98</sup>. In these regions, livestock units have increased by 25% from 1993 to 2013; however, the growth in consumption has led to animal food and feed imports of around 32% of the total food import in 2014, and continues to increase<sup>99</sup>. The impacts of climate change on production potential, combined with the growing demand for animal products will increase the food-import dependence of south Mediterranean countries in the coming decades (estimated at around 50% for all food products in the Maghreb<sup>100</sup>).

Fisheries landings have shifted significantly for nearly 60% of the 59 most abundant commercial fish. Most (~70%) declined (on average by 44%), but increases were also found — mostly for species with short lifespans, which seem to have benefited from increased temperature<sup>101</sup>. For six out of eight of the fish species examined, landings per unit of effort are correlated with temperature, indicating the influence on landings when the fishing effect is accounted for<sup>101</sup>. In the Mediterranean, 91% of assessed fish stocks were overfished in 2014<sup>102</sup>. Although fish stocks are climate-sensitive and vulnerable, both climate change and overfishing undermine the future of Mediterranean fisheries<sup>103</sup>.

Fisheries and aquaculture, crucial for food security and the economy of the Mediterranean<sup>81</sup>, are currently impacted most by overfishing and coastal development<sup>104</sup>. Ocean warming and acidification are very likely to impact fisheries more significantly during the coming decades, with more than 20% of exploited fish and marine invertebrates expected to become locally extinct around 2050. Mediterranean countries import more fish products than they export, as a result of the increasing demand for seafood. Despite being major exporters, France, Spain and Italy are the countries with the highest trade deficits for seafood. Global models project that by 2040–2059 more than 20% of exploited fishes and invertebrates currently found in the eastern Mediterranean could become locally extinct due to climate change<sup>105,106</sup>. By 2070–2099, more than half (45) of the 75 endemic Mediterranean species are expected to qualify for the IUCN Red List of Threatened Species, and 14 more could have become extinct<sup>107</sup>. The expected migration of species to cooler areas as the ocean warms<sup>108</sup> is limited in enclosed seas. For this reason, the Mediterranean Sea has been described as a ‘cul-de-sac’ for endemic fishes, including commercial species, facing climate change<sup>107</sup>.

Overall, expected climate and socio-economic changes pose threats for food safety and security in the Mediterranean region. These pressures will not be homogeneous across the region and its production sectors, creating further regional imbalances and disputes. Thus, trade will be a key factor in maintaining food security. The sustainability of food production represents an issue in unfavourable climate and socio-economic conditions. Collaborative management of fisheries and oceanic food resources and sustainable management of the Mediterranean Sea will be increasingly more necessary as unsustainable practices in one country, enhanced by the effects of climate change and land-based pollution, will affect catches in all other countries.

**Human health.** Climate change is one of many drivers affecting health, acting directly (through heat, cold, drought, storms and other forcings) or indirectly (through changes in food provision and quality, air pollution or other aspects of the social and cultural environments). Impacts vary in magnitude and timing as a function of the local environmental conditions and the vulnerability of the human population<sup>109</sup>. In the Mediterranean Basin, regions with particularly strong changes in ambient temperature and notable heatwaves exist along the coasts and in densely populated urban centres<sup>110</sup>.

Heat-related illnesses and fatalities can occur when high ambient temperatures (particularly when combined with a high relative humidity) exceed the body's natural ability to dissipate heat. For example, a recent analysis<sup>111</sup> for Barcelona (Spain) has shown an increased mortality risk due to natural, respiratory and cardiovascular causes for hot nights with temperatures higher than 23 °C. Older adults, young children and people with pre-existing and chronic medical conditions are particularly susceptible to these illnesses and are therefore at high risk for heat-related mortality<sup>112</sup>. Although most Mediterranean populations are relatively acclimatized to high temperatures, an increase in the intensity and frequency of heatwaves, or a shift in seasonality, are significant health risks for vulnerable population groups, including those who live in poverty with substandard housing and restricted access to air-conditioned spaces<sup>113</sup>. The degree to which heat-related morbidity and mortality rates will increase in the next few decades will depend on the adaptive capacity of Mediterranean population groups through acclimatization, adaptation of the urban environment to reduce heat-island effects, implementation of public education programmes and the preparedness of the healthcare system<sup>109</sup>. Increased population life expectancies imply that the health protection of elderly people will become a major challenge for all Mediterranean countries under heatwave conditions. Indeed, increased mortality was found among people over 65 years in Athens, Greece, at high and very high temperatures<sup>114</sup>. During the severe heat wave in France (summer 2003) most of the extra deaths occurred in the elderly population<sup>115</sup>.

Climate change may influence the emergence of vector-borne diseases as the life-cycle dynamics of the vector species, pathogenic organisms and reservoir organisms are all sensitive to weather conditions<sup>116</sup>. The rates of replication, development and transmission of the pathogens depend more strongly on temperature than on other host–pathogen interactions<sup>117</sup>. In recent years, several outbreaks of different vector-borne diseases have been documented in the Mediterranean region<sup>116,118</sup>.

There is high certainty that the recent observed climatic trends will contribute to the future transmission potential of vector-, food- and water-borne diseases in the region<sup>118</sup>. Predicting the consequences of climate change for the severity of infectious diseases and distributions remains a challenge, particularly for vector-borne infections of humans, which are compounded by the complex interactions between hosts, pathogens and vectors or intermediate hosts that make the cumulative influence of climate change on disease outcomes elusive<sup>117,119</sup>. For 2025 and 2050, the areas with elevated probability for West Nile infections (linked to climate change)<sup>120</sup>, will probably expand and eventually include most Mediterranean countries<sup>121</sup>. During recent years, dengue fever cases were reported in several Mediterranean countries, such as Croatia, France, Greece, Italy, Malta, Portugal and Spain. Although most cases were probably imported, in 2010 local transmission of dengue was reported in Croatia and France. During the hot summer of 2017, outbreaks of chikungunya were reported in France and Italy<sup>122</sup>. Today, there is an apparent threat of outbreaks, transmitted by *Aedes* mosquitoes, in the European Mediterranean countries<sup>123,124</sup>.

**Human security.** Security is affected by impacts of extreme events and societal conflict, in other words, by a combination of natural and social processes<sup>125</sup>. Globally, there is a trend towards higher exposure to risk<sup>126</sup>: between 1970 and 2010 the global population grew by 87%, but the population living in flood plains increased by 114% and that in cyclone-prone coastlines by 192%. In the Mediterranean, one-third of the population (about 150 million people) lives close to the sea. A small tidal range and relatively limited storm surges have led to the development of coastal infrastructure, land-use systems and human settlements that are very close to mean sea level<sup>127</sup>. Sea-level rise, which may well exceed recent IPCC estimates and reach more than 1 m in 2100<sup>20</sup>, will have considerable

impact on Mediterranean coastal hazards, despite some expected reduction of marine storminess<sup>128</sup>. High risk for wave overtopping in Northern Mediterranean ports is manifest<sup>129,130</sup>; however, such coastal risks may be even higher along the southern and eastern shores, where adaptive capacity is generally limited by weaker economic and institutional conditions. Port cities with more than one million inhabitants are considered at increasing risk from severe storm-surge flooding, rising sea level and local land subsidence<sup>131</sup>. By 2050, for the lower sea-level rise scenarios and current adaptation measures, cities in the Mediterranean will account for half of the 20 global cities with the highest increase in average annual damages<sup>132</sup>. Those areas at extremely high risk are predominantly located in the southern and eastern Mediterranean region, including Morocco, Algeria, Libya, Egypt, Palestine and Syria<sup>133</sup>, most of which are presently subject to political instability and thus less able to deal with the additional environmental pressures. In North African countries, 1 m of sea-level rise would impact approximately 41,500 km<sup>2</sup> of the territory and at least 37 million people (~11%)<sup>134</sup>. It is currently not possible to reconcile these estimates with European estimates<sup>135</sup> for a full Mediterranean assessment, but they indicate the potential magnitude of the problem in terms of the number of people who could be impacted by coastal risks.

Coastal areas suffer from the intrusion of salt water and this will increase as sea level rises. In Egypt, about 30% of the irrigated farmlands are affected by salt intrusion<sup>136</sup>. Of the Northern cultivated land, and both Middle and Southern Delta regions, 60% and 20% are considered salt-affected soils, respectively<sup>137</sup>. This environmental degradation pushes Egypt's increasing population into more and more concentrated areas<sup>138</sup>.

Away from the coast, additional risks are associated with increasing wildfires caused by warming, drought and land abandonment. The combined climate and non-climate related forcings have the potential to induce large-scale human migration towards safer areas. Rapid onset events — such as floods or other natural disasters — are clearly linked to immediate environmentally induced displacement and relocation. In contrast, impacts of slower changes, such as mean sea-level rise or the gradual reduction of fresh water availability, are more indirect. Nonetheless, over time there is the potential to trigger permanent population migration at significant scales unless protective measures establishing an acceptable safety level are put in place<sup>139</sup>.

Droughts or changes in ecosystem service supply may also aggravate social conflict and trigger forced migration. Efforts to mitigate one risk may reduce the resilience of human communities or accentuate other risks where resources are limited. Due to its cultural, geopolitical and economic complexity, the Mediterranean Basin has historically been a region of social and political instability. The additional climate-related stressors create increased risks to human security in the region, make communities in the Mediterranean Basin more vulnerable and hence increase human insecurity<sup>140</sup>. Mismanagement and the overexploitation of natural resources during the past century have also contributed to increased vulnerability. The main underlying reasons are the advanced depletion of on- and offshore natural resources, northward-advancing desertification with decreasing water supplies and consequent food insecurity (particularly in the Middle East and North Africa) and the affluence gap between developed, and thus more attractive, European nations, and their much less developed Middle Eastern and North African neighbours with their colonial past underpinning mistrust and separation<sup>141,142</sup>.

For the most recent example of such risks — the several severe, unprecedented and persistent droughts with subsequent income losses in the farming sector in Syria — there is debate about the degree to which recent climate change has contributed to social conflicts and war<sup>143</sup>. However, one widely shared view is that although these droughts are unlikely to have been the direct cause of

conflicts, they could have significantly worsened human livelihoods in the region<sup>1</sup> and have thereby driven more people to migrate.

### Need for a pan-Mediterranean integrated risk assessment

Emergent risks from the interaction between impacts across sectors were identified in IPCC AR5, as well as the consequences of adaptation and mitigation actions at global scale<sup>144</sup>. The Mediterranean Basin provides a particularly strong regional case for such risks, as these may amplify each other or simply absorb significant resources by their superposition. For example, the direct impacts of climate change on agriculture, water supply and fisheries are amplified by the consequences of biodiversity loss on ecosystem services (pollinators, nutrient cycling, water purification). Several risks are also amplified by direct human action through the inefficient management of water, land and marine resources. Although health impacts largely arise due to exposure and vulnerability, they are enhanced by climate change. Urban and low-lying coastal areas are more at risk than other settled regions because of the direct impacts of sea-level rise, but also because of the potentially high infrastructural and socio-economic losses. Social and political instability contribute to climate vulnerability, particularly for impoverished population groups and for states in which the political and social context sets strong limits for efforts to adapt to climate change and mitigate its local impacts. Global teleconnections may also play a major role in the region, both in the climate system (Antarctic glacier destabilization leading to sea-level rise) and in the economic system. Examples include changes to the food commodity market that are driven by crop failures and enhanced yield variability elsewhere, and climate refugees relocating from non-Mediterranean regions such as sub-Saharan Africa. Governance options for collaborative adaptation and mitigation activities are limited by economic disparities, as well as by the existence of failing states, in the region.

At the global scale, critical limits and safe operating spaces are now estimated for multiple impact sectors<sup>145</sup>. However, despite considerable amounts of available information, it remains a challenge to quantify such critical limits for the Mediterranean, for two reasons. First, scaling of global trends to the regional level could underestimate impacts significantly because warming and drying occur faster in the Mediterranean region than at the global scale. Second, socio-economic and political instabilities are mounting in several Mediterranean countries, reducing coordinated action, and diminishing both resilience and the capacity to adapt to environmental change. A comprehensive and coherent assessment of the combined risks has not been undertaken; yet it is urgently needed.

Observations and the scientific capacity for risk assessment are available around the Mediterranean, but resources are unevenly distributed and some of the most vulnerable regions and economic sectors are insufficiently studied. Decision-makers have inadequate access even to the existing knowledge. This may be a result of insufficient networking and exchange between experts — caused by several factors, including cultural, political and language barriers. To contribute to overcoming these barriers, to identify knowledge gaps and to provide unbiased information to policymakers, an international network of more than 400 scientists has been established: the Mediterranean Experts on Environmental and Climate Change (MedECC, <http://www.medecc.org/>). The group works in close contact with intergovernmental agencies, such as the Climate Experts Group of the Union for the Mediterranean and the Barcelona Convention. The group maintains its independence by defining the topical agenda for its interdisciplinary and intersectoral assessment, with the ambition of operating in a similar manner to international science–policy interfaces, such as the IPCC or the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES). A full analysis of the existing scientific literature, covering all societal domains potentially impacted by environmental

change, is underway, to provide an unbiased assessment that targets the information needs expressed by policymakers.

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### References

1. Kelley, C. P. et al. Climate change in the Fertile Crescent and implication of the recent Syrian drought. *Proc. Natl Acad. Sci. USA* **112**, 3241–3246 (2015).  
**Analyses recent drought episodes in Syria and neighbouring countries and suggests a link to economic and political instability.**
2. Hartmann, D. L. et al. in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. et al.) Ch. 2 (IPCC, Cambridge Univ. Press, 2013).
3. Vicente-Serrano, S. M. et al. Evidence of increasing drought severity caused by temperature rise in southern Europe. *Environ. Res. Lett.* **9**, 044001 (2014).
4. Macias, D., Garcia-Goriz, E. & Stips, A. Understanding the causes of recent warming in Mediterranean waters. How much could be attributed to climate change? *PLoS ONE* **8**, e81591 (2013).
5. Tsimplis, M. N. et al. The effect of the NAO on sea level and on mass changes in the Mediterranean Sea. *J. Geophys. Res. Oceans* **118**, 944–952 (2013).  
**Demonstrates the relative contribution of multiple forcings to Mediterranean sea-level changes for the period 1993–2011.**
6. Calafat, F. M. & Gomis, D. Reconstruction of Mediterranean sea level fields for the period 1945–2000. *Glob. Planet. Change* **66**, 225–234 (2009).
7. Meyssignac, B. et al. Two-dimensional reconstruction of the Mediterranean sea level over 1970–2006 from tide gauge data and regional ocean circulation model outputs. *Glob. Planet. Change* **77**, 49–61 (2011).
8. Meier, K. J. S., Beaufort, L., Heussner, S. & Ziveri, P. The role of ocean acidification in *Emiliania huxleyi* coccolith thinning in the Mediterranean Sea. *Biogeosciences* **11**, 2857–2869 (2014).
9. Kapsenberg, L., Alliouane, S., Gazeau, F., Mousseau, L. & Gattuso, J.-P. Coastal ocean acidification and increasing total alkalinity in the northwestern Mediterranean Sea. *Ocean Sci.* **13**, 411–426 (2017).
10. Lionello, P. & Scarascia, L. The relation between climate change in the Mediterranean region and global warming. *Reg. Environ. Change* **18**, 1481–1493 (2018).
11. Seneviratne, S. I., Donat, M. G., Pitman, A. J., Knutti, R. & Wilby, R. L. Allowable CO<sub>2</sub> emissions based on regional and impact-related climate targets. *Nature* **529**, 477–483 (2016).  
**Relates global CO<sub>2</sub> emission trajectories to regional climate change and climate impacts, for the Mediterranean Basin and also for other regions.**
12. Jacob, D. et al. EURO-CORDEX: new high-resolution climate change projections for European impact research. *Reg. Environ. Change* **14**, 563–578 (2014).
13. Zittis, G., Hadjinicolaou, P., Fnais, M. & Lelieveld, J. Projected changes in heat wave characteristics in the eastern Mediterranean and the Middle East. *Reg. Environ. Change* **16**, 1863–1876 (2015).
14. Vautard, R. et al. The European climate under a 2 °C global warming. *Environ. Res. Lett.* **9**, 034006 (2014).
15. Forzieri, G. et al. Ensemble projections of future streamflow droughts in Europe. *Hydrol. Earth Syst. Sci.* **18**, 85–108 (2014).
16. Schleussner, C.-F. et al. Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C. *Earth Syst. Dynam.* **7**, 327–351 (2016).
17. Toreti, A. et al. Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 models. *Geophys. Res. Lett.* **40**, 4887–4892 (2013).
18. Toreti, A. & Naveau, P. On the evaluation of climate model simulated precipitation extremes. *Environ. Res. Lett.* **10**, 014012 (2015).
19. Church, J. A. et al. in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. et al.) Ch. 13 (IPCC, Cambridge Univ. Press, 2013).
20. Vermeer, M. & Rahmstorf, S. Global sea level linked to global temperature. *Proc. Natl Acad. Sci. USA* **106**, 21527–21532 (2009).
21. Jordà, G. & Gomis, D. On the interpretation of the steric and mass components of sea level variability: the case of the Mediterranean basin. *J. Geophys. Res. Oceans* **118**, 953–963 (2013).
22. DeConto, R. M. & Pollard, D. Contribution of Antarctica to past and future sea-level rise. *Nature* **531**, 591–597 (2016).
23. Le Bars, D. Uncertainty in sea level rise projections due to the dependence between contributors. Preprint at *EarthArXiv*: <https://doi.org/10.17605/OSF.IO/UVW3S> (2018).
24. Adloff, F. et al. Improving sea level simulation in Mediterranean regional climate models. *Clim. Dynam.* **51**, 1167–1178 (2017).
25. Adloff, F. et al. Mediterranean Sea response to climate change in an ensemble of twenty first century scenarios. *Clim. Dynam.* **45**, 2775–2802 (2015).



26. Aucelli, P. P. C. et al. Coastal inundation risk assessment due to subsidence and sea level rise in a Mediterranean alluvial plain (Vulturno coastal plain—southern Italy). *Estuar. Coast. Shelf Sci.* **198B**, 597–609 (2017).
27. Enriquez, A. R., Marcos, M., Alvarez-Ellacuria, A., Orfila, A. & Gomis, D. Changes in beach shoreline due to sea level rise and waves under climate change scenarios: application to the Balearic Islands (western Mediterranean). *Nat. Hazards Earth Syst. Sci.* **17**, 1075–1089 (2017).
28. Magnan, A. K. et al. Implications of the Paris Agreement for the ocean. *Nat. Clim. Change* **6**, 732–735 (2016).
- Comprehensive overview of multiple sensitivities in the global ocean system to various levels of projected climate change.**
29. Palmiéri, J. et al. Simulated anthropogenic CO<sub>2</sub> storage and acidification of the Mediterranean Sea. *Biogeosciences* **12**, 781–802 (2015).
30. *Middle East & North Africa Data* (World Bank Group, accessed 3 September 2017); <https://data.worldbank.org/region/middle-east-and-north-africa>
31. Mueller, N. D. et al. Closing yield gaps through nutrient and water management. *Nature* **490**, 254–257 (2012).
32. Jiménez Cisneros, B. E. et al. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds Field, C. B. et al.) Ch. 3 (IPCC, Cambridge Univ. Press, 2014).
33. Kovats, R. S. et al. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds Field, C. B. et al.) Ch. 23 (IPCC, Cambridge Univ. Press, 2014).
34. Tsanis, I. K., Koutroulis, A. G., Daliakopoulos, I. N. & Jacob, D. Severe climate-induced water shortage and extremes in Crete. *Climatic Change* **106**, 667–677 (2011).
35. Bucak, T. et al. Future water availability in the largest freshwater Mediterranean lake is at great risk as evidenced from simulations with the SWAT model. *Sci. Total Environ.* **581–582**, 413–425 (2017).
36. García-Ruiz, J. M., López-Moreno, J. I., Vicente-Serrano, S. M., Lasanta-Martínez, T. & Beguería, S. Mediterranean water resources in a global change scenario. *Earth Sci. Rev.* **105**(3–4), 121–139 (2011).
37. Ludwig, W., Bouwman, A. F., Dumont, F. & Lespinas, F. Water and nutrient fluxes from major Mediterranean and Black Sea rivers: past and future trends and their implications for the basin-scale budgets. *Glob. Biogeochem. Cycles* **24**, GB0A13 (2010).
- Comprehensive study of hydrological and water quality changes for Mediterranean catchments in the past and for projected future conditions.**
38. Hermoso, V. & Clavero, M. Threatening processes and conservation management of endemic freshwater fish in the Mediterranean basin: a review. *Mar. Freshwat. Res.* **62**, 244–254 (2011).
39. Gonçalves, J., Petersen, J., Deschamps, P., Hamelin, B. & Baba-Sy, O. Quantifying the modern recharge of the “fossil” Sahara aquifers. *Geophys. Res. Lett.* **40**, 2673–2678 (2013).
40. Albiac, J., Esteban, E., Tapia, J. & Rivas, E. in *Drought in Arid and Semi-Arid Regions: A Multi-Disciplinary and Cross-Country Perspective* (eds Schwabe, K. et al.) 323–339 (Springer, Dordrecht, 2013).
41. Iglesias, A., Garrote, L., Quiroga, S. & Moneo, M. From climate change impacts to the development of adaptation strategies: challenges for agriculture in Europe. *Climatic Change* **112**, 143–168 (2012).
42. Fader, M., Shi, S., Von Bloh, W., Bondeau, A. & Cramer, W. Mediterranean irrigation under climate change: more efficient irrigation needed to compensate increases in irrigation water requirements. *Hydrol. Earth Syst. Sci.* **20**, 953–973 (2016).
43. Gaume, E. et al. in *The Mediterranean Region under Climate Change. A Scientific Update* 133–144 (IRD Editions, 2016).
44. Llasat, M. C., Marcos, R., Turco, M., Gilabert, J. & Llasat-Botija, M. Flash floods trends versus convective precipitation in a Mediterranean region. *J. Hydrol.* **541**, 24–37 (2016).
45. Alfieri, L., Burek, P., Feyen, L. & Forzieri, G. Global warming increases the frequency of river floods in Europe. *Hydrol. Earth Syst. Sci.* **19**, 2247–2260 (2015).
46. Kundzewicz, Z. W. et al. Differences in flood hazard projections in Europe—their causes and consequences for decision making. *Hydrol. Sci. J.* **62**, 1–14 (2017).
47. Llasat, M. C. et al. Towards a database on societal impact of Mediterranean floods in the framework of the HYMEX project. *Nat. Hazards Earth Syst. Sci.* **13**, 1–14 (2013).
48. Blöschl, G. et al. Changing climate shifts timing of European floods. *Science* **357**, 588–590 (2017).
49. Guiot, J. & Cramer, W. Climate change: the 2015 Paris Agreement thresholds and Mediterranean basin ecosystems. *Science* **354**, 465–468 (2016).
- Using a process-based ecosystem model fitted to pollen-based vegetation reconstructions, this study demonstrates that only a 1.5 °C global climate trajectory allows Mediterranean land ecosystems to remain in the variability range of the past 10,000 years.**
50. Gouveia, C. M., Trigo, R. M., Beguería, S. & Vicente-Serrano, S. M. Drought impacts on vegetation activity in the Mediterranean region: an assessment using remote sensing data and multi-scale drought indicators. *Glob. Planet. Change* **151**, 15–27 (2017).
51. Santonja, M. et al. Plant litter mixture partly mitigates the negative effects of extended drought on soil communities and litter decomposition in a Mediterranean oak forest. *J. Ecol.* **105**, 801–815 (2017).
52. Duguy, B. et al. in *Regional Assessment of Climate Change in the Mediterranean* Vol. 2 (eds Navarra, A. & Tubiana, L.) 101–134 (Springer, Dordrecht, 2013).
53. Turco, M., Llasat, M. C., von Hardenberg, J. & Provenzale, A. Climate change impacts on wildfires in a Mediterranean environment. *Climatic Change* **125**, 369–380 (2014).
- Distinguishes climatic from non-climatic forcings of Mediterranean fire dynamics.**
54. Ruffault, J., Moron, V., Trigo, R. M. & Curt, T. Objective identification of multiple large fire climatologies: an application to a Mediterranean ecosystem. *Environ. Res. Lett.* **11**, 7 (2016).
55. Zacharias, I. & Zamparas, M. Mediterranean temporary ponds. A disappearing ecosystem. *Biodivers. Conserv.* **19**, 3827–3834 (2010).
- One of only very few studies of Mediterranean freshwater ecosystems under climate change.**
56. Klausmeyer, K. R. & Shaw, M. R. Climate change, habitat loss, protected areas and the climate adaptation potential of species in Mediterranean ecosystems worldwide. *PLoS ONE* **4**, e6392 (2009).
57. Peñuelas, J. et al. Evidence of current impact of climate change on life: a walk from genes to the biosphere. *Glob. Change Biol.* **19**, 2303–2338 (2013).
58. Peñuelas, J. et al. Impacts of global change on Mediterranean forests and their services. *Forests* **8**, 463 (2017).
59. Williams, A. P. et al. Temperature as a potent driver of regional forest drought stress and tree mortality. *Nat. Clim. Change* **3**, 292–297 (2013).
60. Doblas-Miranda, E. et al. A review of the combination among global change factors in forests, shrublands and pastures of the Mediterranean Region: beyond drought effects. *Glob. Planet. Change* **148**, 42–54 (2017).
61. García-Nieto, A. P. et al. Impacts of urbanization around Mediterranean cities: changes in ecosystem service supply. *Ecol. Ind.* **91**, 589–606 (2018).
62. Garrabou, J. et al. Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Glob. Change Biol.* **15**, 1090–1103 (2009).
- Documents climate-driven mass mortality events in marine Mediterranean ecosystems.**
63. Rivetti, I., Fraschetti, S., Lionello, P., Zambianchi, E. & Boero, F. Global warming and mass mortalities of benthic invertebrates in the Mediterranean Sea. *PLoS ONE* **9**, e115655 (2014).
64. Marbà, N., Jorda, G., Agustí, S., Girard, S. C. & Duarte, C. M. Footprints of climate change on Mediterranean Sea biota. *Front. Mar. Sci.* **2**, 56 (2015).
65. *Climate Warming and Related Changes in Mediterranean Marine Biota* Workshop Monograph 35 (ed. Briand, F.) (CIESM, 2008).
66. Azzurro, E., Moschella, P. & Maynou, F. Tracking signals of change in Mediterranean fish diversity based on local ecological knowledge. *PLoS ONE* **6**, e24885 (2011).
67. Lloret, J. et al. How a multidisciplinary approach involving ethnoecology, biology and fisheries can help explain the spatio-temporal changes in marine fish abundance resulting from climate change. *Glob. Ecol. Biogeogr.* **24**, 448–461 (2015).
68. Parravicini, V. et al. Climate change and warm-water species at the northwestern boundary of the Mediterranean Sea. *Mar. Ecol. Evol. Persp.* **36**, 897–909 (2015).
69. Chevaldonné, P. & Lejeune, C. Regional warming-induced species shift in north-west Mediterranean marine caves. *Ecol. Lett.* **6**, 371–379 (2003).
- One of the earliest studies demonstrating impacts of climate fluctuations on northwest Mediterranean marine biota.**
70. Milazzo, M. et al. Warming-related shifts in the distribution of two competing coastal wrasses. *Mar. Environ. Res.* **120**, 55–67 (2016).
71. Galil, B. S., Marchini, A. & Occhipinti-Ambrogi, A. East is east and West is west? Management of marine bioinvasions in the Mediterranean Sea. *Estuar. Coast. Shelf Sci.* **201**, 7–16 (2018).
72. Vergés, A. et al. Tropical rabbitfish and the deforestation of a warming temperate sea. *J. Ecol.* **102**, 1518–1527 (2014).
73. Gattuso, J.-P. et al. Contrasting future for ocean and society from different anthropogenic CO<sub>2</sub> emissions scenarios. *Science* **349**, aac4722 (2015).
74. Hall-Spencer, J. M. et al. Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature* **454**, 96–99 (2008).
75. Kroeker, K. J., Micheli, F., Gambi, M. C. & Martz, T. R. Divergent ecosystem responses within a benthic marine community to ocean acidification. *Proc. Natl Acad. Sci. USA* **108**, 14515–14520 (2011).
76. Linares, C. et al. Persistent acidification drives major distribution shifts in marine benthic ecosystems. *Proc. R. Soc. B* **282**, 20150587 (2015).



77. Rodrigues, L. C. et al. Sensitivity of Mediterranean bivalve mollusc aquaculture to climate change, ocean acidification, and other environmental pressures: findings from a producer survey. *J. Shellfish Res.* **34**, 1161–1176 (2015).
78. Lique, C., Piroddi, C., Macias, D., Druon, J.-N. & Zulian, G. Ecosystem services sustainability in the Mediterranean Sea: assessment of status and trends using multiple modelling approaches. *Sci. Rep.* **6**, 34162 (2016).  
**One of the earliest comprehensive assessments of ecosystem service provisioning changes in the Mediterranean Sea.**
79. Martín-López, B. et al. in *Routledge Handbook of Ecosystem Services* (eds Potschin, M. et al.) 405–414 (Routledge, London, 2016).
80. Paciello, M. C. (ed.) *Building Sustainable Agriculture for Food Security in the Euro-Mediterranean Area: Challenges and Policy Options* (IAI & OCP, 2015).
81. Piante, C. & Ody, D. *Blue Growth in the Mediterranean Sea: The Challenge of Good Environmental Status* (MedTrends Project, WWF-France, 2015).
82. Deryng, D. et al. Regional disparities in the beneficial effects of rising CO<sub>2</sub> concentrations on crop water productivity. *Nat. Clim. Change* **6**, 786–790 (2016).
83. Giannakopoulos, C. et al. Climatic changes and associated impacts in the Mediterranean resulting from a 2 °C global warming. *Glob. Planet. Change* **68**, 209–224 (2009).
84. Tanasijevic, L. et al. Impacts of climate change on olive crop evapotranspiration and irrigation requirements in the Mediterranean region. *Agric. Water Manage.* **144**, 54–68 (2014).
85. Gabaldón-Leal, C. et al. Impacts of changes in the mean and extreme temperatures caused by climate change on olive flowering in southern Spain. *Int. J. Climatol.* **37**, 940–957 (2017).
86. Ponti, L., Gutierrez, A. P., Ruti, P. M. & Dell'Aquila, A. Fine-scale ecological and economic assessment of climate change on olive in the Mediterranean Basin reveals winners and losers. *Proc. Natl Acad. Sci. USA* **111**, 5598–5603 (2014).
87. Fraga, H., García de Cortázar Atauri, I., Malheiro, A. C. & Santos, J. A. Modelling climate change impacts on viticultural yield, phenology and stress conditions in Europe. *Glob. Change Biol.* **22**, 3774–3788 (2016).
88. Funes, I. et al. Future climate change impacts on apple flowering date in a Mediterranean subbasin. *Agric. Water Manage.* **164**, 19–27 (2016).
89. Arbex de Castro Vilas Boas, A., Page, D., Giovino, R., Bertin, N. & Fanciullino, A.-L. Combined effects of irrigation regime, genotype, and harvest stage determine tomato fruit quality and aptitude for processing into puree. *Front. Plant Sci.* **8**, 1725 (2017).
90. Barbagallo, R. N., Di Silvestro, I. & Patané, C. Yield, physicochemical traits, antioxidant pattern, polyphenol oxidase activity and total visual quality of field-grown processing tomato cv. Brigade as affected by water stress in Mediterranean climate. *J. Sci. Food Agric.* **93**, 1449–1457 (2013).
91. Fitzgerald, G. J. et al. Elevated atmospheric [CO<sub>2</sub>] can dramatically increase wheat yields in semi-arid environments and buffer against heat waves. *Glob. Change Biol.* **22**, 2269–2284 (2016).
92. Fernando, N. et al. Rising CO<sub>2</sub> concentration altered wheat grain proteome and flour rheological characteristics. *Food Chem.* **170**, 448–454 (2015).
93. Miraglia, M. et al. Climate change and food safety: an emerging issue with special focus on Europe. *Food Chem. Toxicol.* **47**, 1009–1021 (2009).
94. Link, P. M., Kominek, J. & Scheffran, J. Impacts of sea level rise on the coastal zones of Egypt. *Main. Geogr. Stud.* **55**, 79–94 (2012).
95. Bernués, A., Ruiz, R., Olazola, A., Villalba, D. & Casasus, I. Sustainability of pasture-based livestock farming systems in the European Mediterranean context: synergies and trade-offs. *Livest. Sci.* **139**, 44–57 (2011).  
**Comprehensive analysis of Mediterranean livestock system changes subjected to global change forcings.**
96. Herrero, M. & Thornton, P. K. Livestock and global change: emerging issues for sustainable food systems. *Proc. Natl Acad. Sci. USA* **110**, 20878–20881 (2013).
97. Herrero, M. et al. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc. Natl Acad. Sci. USA* **110**, 20888–20893 (2013).
98. Weindl, I. et al. Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. *Environ. Res. Lett.* **10**, 094021 (2015).
99. FAO Livestock contribution to food security in the Near East and North Africa. In *FAO Regional Conference for the Near East, 33th Session* (FAO, 2016); <http://www.fao.org/3/a-mp852e.pdf>
100. *Addressing Agricultural Import Dependence in the Middle East-North Africa Region Through the Year 2050* (INRA & Pluriagri, 2015).
101. Tzanatos, E., Raitos, D. E., Triantafyllou, G., Somarakis, S. & Tsonis, A. A. Indications of a climate effect on Mediterranean fisheries. *Climatic Change* **122**, 41–54 (2014).
102. *Maritime Affairs and Fisheries: On the State of Fish Stocks* (EC, 2014); <https://go.nature.com/2OWQJHr>
103. Coll, M. et al. The Mediterranean Sea under siege: spatial overlap between marine biodiversity, cumulative threats and marine reserves. *Glob. Ecol. Biogeogr.* **21**, 465–480 (2012).
104. *Communication from the Commission to the European Parliament and the Council Concerning a Consultation on Fishing Opportunities for 2015 Under the Common Fisheries Policy* (EC, 2014).
105. Jones, M. C. & Cheung, W. W. L. Multi-model ensemble projections of climate change effects on global marine biodiversity. *ICES J. Mar. Sci.* **72**, 741–752 (2015).
106. Cheung, W. W. L. et al. Structural uncertainty in projecting global fisheries catches under climate change. *Ecol. Model.* **325**, 57–66 (2016).
107. Ben Rais Lasram, F. et al. The Mediterranean Sea as a 'cul-de-sac' for endemic fishes facing climate change. *Glob. Change Biol.* **16**, 3233–3245 (2010).
108. Poloczanska, E. S. et al. Responses of marine organisms to climate change across oceans. *Front. Mar. Sci.* **3**, 62 (2016).
109. Smith, K. R. et al. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds Field, C. B. et al.) Ch. 11 (IPCC, Cambridge Univ. Press, 2014).
110. Kuglitsch, F. G. et al. Heat wave changes in the eastern Mediterranean since 1960. *Geophys. Res. Lett.* **37**, L04802 (2010).
111. Royé, D. The effects of hot nights on mortality in Barcelona. *Int. J. Biometeorol.* **61**, 2127–2140 (2017).
112. Heat Stress (CDC, 2015); <http://www.cdc.gov/niosh/topics/heatstress>
113. Paz, S., Negev, M., Clermont, A. & Green, M. S. Health aspects of climate change in cities with Mediterranean climate, and local adaptation plans. *Int. J. Environ. Res. Public Health* **13**, 438 (2016).
114. Paravantis, J., Santamouris, M., Cartalis, C., Efthymiou, C. & Kontoulis, N. Mortality associated with high ambient temperatures, heatwaves, and the urban heat island in Athens, Greece. *Sustainability* **9**, 606 (2017).
115. Fouillet, A. et al. Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. *Int. J. Epidemiol.* **37**, 309–317 (2008).
116. Parham, P. E. et al. Climate, environmental and socio-economic change: weighing up the balance in vector-borne disease transmission. *Phil. Trans. R. Soc. Lond. B* **370**, 20130551 (2015).
117. Altizer, S., Ostfeld, R. S., Johnson, P. T., Kutz, S. & Harvell, C. D. Climate change and infectious diseases: from evidence to a predictive framework. *Science* **341**, 514–519 (2013).
118. Negev, M. et al. Impacts of climate change on vector borne diseases in the Mediterranean Basin: implications for preparedness and adaptation policy. *Int. J. Environ. Res. Pub. Health* **12**, 6745–6770 (2015).
119. Rohr, J. R. et al. Frontiers in climate change–disease research. *Trends Ecol. Evol.* **26**, 270–277 (2011).
120. Paz, S. et al. Permissive summer temperatures of the 2010 European West Nile Fever upsurge. *PLoS ONE* **8**, e56398 (2013).
121. Semenza, J. C. et al. Climate change projections of West Nile Virus infections in Europe: implications for blood safety practices. *Environ. Health* **15** (Suppl. 1), 28 (2016).
122. *Clusters of Autochthonous Chikungunya Cases in Italy, First Update — 9 October 2017* (ECDC, 2017); <https://go.nature.com/2xYz7DI>
123. *The Climatic Suitability for Dengue Transmission in Continental Europe* (ECDC, 2012); <https://go.nature.com/2In38BK>
124. *Annual Epidemiological Report 2016: Dengue Fever* (ECDC, 2016); <https://go.nature.com/2OV7nHe>
125. Adger, W. N. et al. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds Field, C. B. et al.) Ch. 12 (IPCC, Cambridge Univ. Press, 2014).
126. Hallegatte, S. *An Exploration of the Link Between Development, Economic Growth, and Natural Risk* (World Bank, 2014).
127. Becker, A., Inoue, S., Fischer, M. & Schwegler, B. Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port administrators. *Climatic Change* **110**, 5–29 (2012).
128. Lionello, P., Conte, D., Marzo, L. & Scarascia, L. The contrasting effect of increasing mean sea level and decreasing storminess on the maximum water level during storms along the coast of the Mediterranean Sea in the mid 21st century. *Glob. Planet. Change* **151**, 80–91 (2016).
129. Sanchez-Arcilla, A. et al. A review of potential physical impacts on harbours in the Mediterranean Sea under climate change. *Reg. Environ. Change* **16**, 2471–2484 (2016).
130. Sierra, J. P., Casanovas, I., Mössö, C., Mestres, M. & Sanchez-Arcilla, A. Vulnerability of Catalan (NW Mediterranean) ports to wave overtopping due to different scenarios of sea level rise. *Reg. Environ. Change* **16**, 1457–1468 (2016).
131. Nicholls, R. J. et al. *Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates Environment Working Paper No. 1* (OECD Publishing, 2008).
132. Hallegatte, S., Green, C., Nicholls, R. J. & Corfee-Morlot, J. Future flood losses in major coastal cities. *Nat. Clim. Change* **3**, 802–806 (2013).

133. Satta, A., Puddu, M., Venturini, S. & Giupponi, C. Assessment of coastal risks to climate change related impacts at the regional scale: the case of the Mediterranean region. *Int. J. Disast. Risk Reduct.* **24**, 284–296 (2017).
134. Tolba, M. K. & Saab, N. W. *Impact of Climate Change on Arab Countries* (AFED, 2009).
135. Ciscar, J. C. et al. *Climate Impacts in Europe: The JRC PESETA II Project EUR 26586EN* (JRC, EC, 2014); <https://go.nature.com/2ln0CLO>
136. Hegazi, A. M., Afifi, M. Y., Elwan, A. A., Shorbagy, M. A. E. L. & El-Demerdashe, S. (eds) *Egyptian National Action Program to Combat Desertification* (Desert Research Center, Ministry of Agriculture and Land Reclamation, 2005); <http://www.unccd.int/ActionProgrammes/egypt-eng2005.pdf>
137. Rubio, J. L., Safriel, U., Daussa, R., Blum, W. & Pedrazzini, F. *Water Scarcity, Land Degradation and Desertification in the Mediterranean Region* (NATO Science for Peace and Security Series C: Environmental Security, Springer, 2009).
138. Abahussain, A. A. et al. Desertification in the Arab Region: analysis of current status and trends. *J. Arid Environm.* **51**, 521–545 (2002).
139. Renaud, F., Dun, O., Warner, K. & Bogardi, J. A decision framework for environmentally induced migration. *Int. Migrat.* **49**(S1), e5–e29 (2011).
140. Gleick, P. H. Water, drought, climate change, and conflict in Syria. *Weather Clim. Soc.* **6**, 331–340 (2014).
141. Warner, K. et al. in *Climate Change: Addressing the Impact on Human Security* (ed. Dokos, T.) 62–84 (Hellenic Republic, Ministry of Foreign Affairs, 2008).
142. Wodon, Q., Liverani, A., Joseph, G. & Bougnoux, N. (eds) *Climate Change and Migration: Evidence from the Middle East and North Africa* (World Bank, 2014).
143. Brzoska, M. & Fröhlich, C. Climate change, migration and violent conflict: vulnerabilities, pathways and adaptation strategies. *Migrat. Dev.* **5**, 190–210 (2016).
144. Oppenheimer, M. et al. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds Field, C. B. et al.) Ch. 19 (IPCC, Cambridge Univ. Press, 2014).
145. Steffen, W. et al. Planetary boundaries: guiding human development on a changing planet. *Science* **347**, 6223 (2015).
146. *Sea Water Desalination: To What Extent is it a Freshwater Solution in the Mediterranean?* (Plan Bleu, 2010).

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## Author contributions

W.C. and J.G. developed the assessment protocol and convened the author team. All authors contributed sectoral knowledge and text. W.C. wrote the paper.

## Competing interests

The authors declare no competing interests.