Interlinking climate change with the Water - Energy - Food - Ecosystems (WEFE) nexus in the Mediterranean Basin

by MedECC
Mediterranean Experts on Climate and environmental Change

Union for the Mediterranean
Union pour la Méditerranée
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Special Report

Interlinking climate change with the Water - Energy - Food - Ecosystems (WEFE) nexus in the Mediterranean Basin

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Foreword

The Mediterranean region is currently dealing with critical global challenges, including water scarcity, food and energy insecurity, and ecosystem degradation. These challenges are interconnected and are collectively referred to as the Water-Energy-Food-Ecosystems (WEFE) nexus. Climate change further exacerbates these challenges, making it necessary to take a comprehensive and integrated approach to achieve sustainable development and resilience in the face of evolving environmental and socio-economic dynamics.

This Special Report on the WEFE nexus is essential. It represents a significant step in understanding the complex relationships between water, energy, food, and ecosystems in the Mediterranean. The report is based on assessment frameworks developed by the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). It offers a comprehensive assessment of the available scientific knowledge on these issues, covering the drivers of change, cascading impacts, and response options for addressing the multiple challenges in the region. The report emphasises the need for cross-sectoral coordination, technological and social innovation, ecosystem-based solutions, including nature-based, and transformative governance to mitigate risks and maximise synergies across the WEFE components.

This report aligns with the most recent IPCC findings on climate impacts, focusing on the Mediterranean region, and adapts the IPBES context to emphasise the crucial role of ecosystems in ensuring water, food, and energy security. It stresses the importance of employing a nexus approach at various scales – from local to regional – to build resilience, promote peace, and support the achievement of the Sustainable Development Goals (SDGs).

The findings in this Special Report are the result of collaborative efforts by scientists, policymakers, and stakeholders across the Mediterranean. It builds on the First Mediterranean Assessment Report (MAR1) released in 2020 by MedECC, advancing the discussion by focusing on the interconnections and trade-offs between water, energy, food, and ecosystems. This report provides decision-makers with data-driven insights, along with evaluations relevant for policy-making needed for mitigating climate impacts and ensuring the sustainable management of natural resources.

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Statements from Key Partners

This new MedeCC special report on the nexus or interaction between water, environment, food and energy (WEFE) sheds light on a vital aspect of Mediterranean life. The growing water shortage in the Basin is threatening the survival of the environment and agriculture around the Big Blue. It is the very life of the Mediterranean people that is at stake, their ability to ensure their food security. The countries on the southern shores of the Mediterranean are already bearing the full brunt of repeated spring and summer droughts, with torrential rains following in the autumn. The threat is rising in latitude, and Europe is now under the spotlight.

Technology, and in particular the desalination of seawater using renewable energy sources, may offer ways of adapting, but let's make no mistake: we need to rethink the management of the great water cycle, questioning not only supply but also uses.
It is fundamental.

Mr Robin Degron
Director of Plan Bleu (UNEP/MAP)

Climate change presents multiple challenges to the water, energy, food, and ecosystems (WEFE) nexus in the Mediterranean region. Rising temperatures, evolving precipitation patterns, and more frequent extreme weather events threaten water availability, agricultural productivity, energy security, and ecosystem health across the region. This new report addresses the critical need to understand and manage the intricate links between climate change and the WEFE nexus in the Mediterranean. By examining how climate stressors impact each component of this nexus and how they interrelate, it offers a comprehensive overview of the current challenges while highlighting solutions to enhance resilience and sustainability, thus contributing to the objectives of the UNEP/MAP Mediterranean Strategy for Sustainable Development.

It emphasizes the importance of integrated management approaches that account for the interdependencies within the WEFE nexus to develop adaptive strategies for mitigating climate impacts. The report, compiled by voluntary scientists within the network of Mediterranean Experts on Climate and environmental Change (MedECC), and engaging policymakers, represents an invaluable contribution to the science-policy dialogue in the Mediterranean and to support evidence-based decision-making. The UNEP/MAP is pleased to renew its support for MedECC, with activities included in the UNEP/MAP work programs for 2024-2025."

Ms Tatjana Hema
UNEP/MAP Coordinator

As we confront the interconnected challenges of climate change, this report on the Water-Energy-Food-Ecosystems (WEFE) nexus sends the clear and urgent message: the time for action is now. The Mediterranean, a high-risk region, faces severe pressures. Water scarcity is deepening, energy demand is mounting, food security is under threat, and ecosystems are being pushed to the brink of collapse. The consequences of inaction will profoundly impact millions of lives and destabilise our economies. This report serves as a strong call for action for political leaders and stakeholders throughout the region. It emphasises the need for innovative and integrated solutions, including renewable energy technologies, ecosystem-based approaches, and social strategies to promote sustainable practices. It also advocates for enhanced institutional capacities and improved science-policy interface to ensure coordinated actions across sectors. The Union for the Mediterranean is committed to leading this change and facilitating regional cooperation to address these pressing challenges. However, this can only be achieved with firm commitment from all parties involved. The Mediterranean must transform from a "hot spot" of climate troubles to a "hope spot" for sustainable development, a shift that requires decisive leadership and immediate action. We must unite and tackle these interconnected challenges with ambition and determination to enhance resilience, safeguard resources and work towards a sustainable future for the Mediterranean.

Mr Nasser Kamel
Secretary General of the Union for the Mediterranean (UfM)

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The MedECC report is the result of extensive efforts by numerous individuals, supported by esteemed institutions. We express our deepest appreciation to the Coordinating Lead Authors and Lead Author for their invaluable expertise and dedication throughout the process. Their work was facilitated by the many Contributing Authors, who assisted in drafting the report. We are grateful to the experts and government reviewers whose insightful feedback on the drafts significantly enhanced the report's quality.

We sincerely acknowledge the support from the contributing institutions, particularly Plan Bleu, which hosts the MedECC Secretariat, the Union for the Mediterranean (UfM) (with funding from the Swedish International Development Cooperation Agency (SIDA)), and the United Nations Environment Programme/Mediterranean Action Plan (UNEP/MAP). The MedECC also benefits from the funding from the French Agency for Ecological Transition (ADEME), the French Ministry of Ecological Transition and Territorial Cohesion, the French Ministry for Europe and Foreign Affairs (MEAE), the Italian Ministry of Environment and Energy Security (MASE), the Principality of Monaco, the French Rhone Mediterranean Corsica water agency, and the Mediterranean Trust Fund (MTF). MedECC is also supported by the Advisory Council for the Sustainable Development of Catalonia (Government of Catalonia, Spain), the Association pour l'innovation et la recherche au service du climat (AIR Climat) and IT Department of OSU Pythéas (France).

We would like to extend our special recognition to individuals who provided invaluable help in advancing MedECC and its science-policy interface, especially Robin Degron and François Guerquin, current and former Director of Plan Bleu, Lina Tode, former Deputy Director of Plan Bleu and Antoine Lafitte, Director of the Observatory and Relations with UNEP/MAP at Plan Bleu; Grammenos Mastrojeni, Deputy Secretary General for Energy and Climate Action (UfM Secretariat); Marie-Claire Boillot, Senior Expert on Energy and Climate Action (UfM Secretariat); Arnault Graves, former Senior Climate Adviser (UfM Secretariat). We also acknowledge the UNEP/MAP Coordinating Unit, especially Coordinator Tatjana Hema, as well as Ilias Mavroeidis and Julien le Tellier, current and former Programme Management Officer respectively.

We gratefully thank the following individuals who provided their invaluable help and assistance for the Coordinating Lead Authors in person meeting, held in Barcelona (Spain) in June 2022: Arnau Queralt Bassat (Advisory Council for the Sustainable Development of Catalonia, Government of Catalonia, Spain) and Maria Carmen Llasat (University of Barcelona, Spain), Sandra Dubelcco and Yasmine Hadj Larbi (Plan Bleu).

The refinement of the Summary for Policymakers (SPM) was further enhanced by a day-long discussion with stakeholders, including governmental Focal Points, chaired by Marie-Claire Boillot (UfM) and Antoine Lafitte (Plan Bleu).

We are grateful to those involved in communicating about MedECC and its reports, including the Plan Bleu communication team, especially Pauline Simon, Christelle El Selfani, and Chloé Gaillard, as well as the UfM communication team, especially Isabel Pardillos.

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Preface

MedECC

The Mediterranean Experts on Climate and environmental Change (MedECC) is an open and independent network of scientists founded in 2015, that specifically focuses on climate and environmental changes within the Mediterranean region. The objective of MedECC is to provide decision-makers, stakeholders, and citizens with scientific assessments of scientific knowledge on climate and environmental changes including associated risks and social aspects.

To date (October 2024) more than 300 authors contributed to MedECC reports in an individual capacity and without financial compensation. MedECC scientists are located in 35 countries, including 19 registered as Contracting Parties to the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (Barcelona Convention) and 23 members of the Union for the Mediterranean (UfM).

The network is governed by Co-Coordinators, a Steering Committee, and an Advisory Board. The operations are managed by the MedECC Secretariat, which is officially hosted by Plan Bleu, a UNEP/MAP Regional Activity Centre in Marseille, France, as part of a partnership with the Secretariat of the Union for the Mediterranean (UfM). The Mediterranean Action Plan of the United Nations Environment Program (UNEP/MAP) has also provided support since 2022, with MedECC activities integrated into the UNEP/MAP Work Programmes for 2022-2023 and 2024-2025, approved during COP 22 (Antalya, Türkiye, December 2021) and COP 23 (Portorož, December 2023). The UfM supports MedECC through technical assistance contracts for the MedECC via the AIR Climat association (2018-2020, 2021-2023 and 2024-2026) thanks to the funding from the Swedish International Development Cooperation Agency (SIDA).

The MedECC published the First Mediterranean Assessment Report (MAR1) in November 2020, which includes a Summary for Policymakers (SPM) that has been approved line by line during a plenary session attended by government representatives from Mediterranean countries in September 2020. The SPM was recognised as an important contribution of the scientific community to future climate and environmental action in the Mediterranean region in the Declaration adopted during the 2nd Union for the Mediterranean Ministerial Meeting on Climate and Environmental Action (October 4, 2021, Cairo, Egypt), and was endorsed by the Contracting Parties to the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (Barcelona Convention) and its Protocols at their 22nd meeting (COP 22, December 2021, Antalya, Türkiye). MedECC was awarded the prestigious North-South Prize 2020 of the Council of Europe for their efforts for peace and democracy. The MAR1 report has significantly laid the groundwork for the first ever chapter on the Mediterranean Basin in an IPCC report, published as a cross-chapter paper in the IPCC 6th Assessment Report in 2022. The findings of MAR1 have been recognised in several key strategic documents aimed at mitigating climate impacts and informed by scientific knowledge from MAR1. The Portorož Ministerial Declaration, signed by the Ministers of the Environment and Heads of Delegation of the Contracting Parties to the Barcelona Convention during COP 23, held from December 5-8, 2023, in Portorož, Slovenia (Decision UNEP/MED IG.26), emphasises the need to enhance actions against climate change in the Mediterranean and to protect marine ecosystems from its harmful impacts. It calls for strengthening scientific knowledge and expertise in this area, highlighting initiatives like MedECC.

This Special Report

The Special Report "Interlinking climate change with water - energy - food - ecosystems nexus in the Mediterranean Basin" responds to the MedECC Steering Committee's decision to produce three Special Reports as part of the 2021-2023 MedECC work programme. These reports focus on specific issues identified after the publication of the First Mediterranean Assessment Report (MAR1) in November 2020, including considering suggestions from government representatives and stakeholders. As all MedECC reports, this report is produced for use by policymakers and a broader audience. It is developed on the basis of scientific criteria only. The Special Report provides a comprehensive assessment of the scientific and technical literature. It builds upon the MedECC MAR1 Assessment Report, previous report by Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem

Services (IPBES) reports, as well as other relevant regional, national and local assessments, and is drawing on evidence from over 1000 scientific publications. The available knowledge concerning the risks studied by MedECC has significant gaps, often due to limited monitoring systems or scientific research capacity – these gaps have been communicated as clearly as possible. Despite best efforts, errors and omissions are nevertheless not unlikely.

Scope of the Report

This Special Report identifies and assesses the impact of environmental and climate change on the Water-Energy-Food-Ecosystems (WEFE) nexus in the Mediterranean Basin, related risks, adaptation options and solutions along five chapters. In this report, the WEFE nexus is addressed as a key concept for a more resilient adaptation to the climate crisis in the Mediterranean region. It addresses the interlinked water, energy and food security – and their connection with the surrounding ecosystems. Thus, security issues, and therefore adaptation actions, are the key focus of this report, leaving the mitigation consequences of the nexus approach as potential synergies and trade-offs derived from the interconnections among WEFE components. The focus is on the nexus between water, energy and food security and ecosystems' health, extending to the coasts of the Mediterranean Sea, and the report does not address the details of marine environment.

Structure of the Report

This report consists of five Chapters, four Annexes, and includes a Summary for Policymakers (SPM) composed of headline statements, a high-level summary and narrative of the key messages from the longer report. Chapter 1 provides the context, background and key dimensions of this assessment, Chapter 2 assesses the drivers of change impacting on the WEFE nexus and the cascading effects associated to these impacts, Chapter 3 assesses the existing and prospective responses and management options to implement the WEFE nexus approach in the context of climate change. Chapter 4 addresses the link between the WEFE approach and the Sustainable Development Goals (SDG). Finally, Chapter 5 reviews governance, policies and research options for the WEFE nexus implementation in the Mediterranean Basin.

The Process

The Special Report represents the collaborative efforts of a team of volunteer leading experts and scientists in the various related fields of research. Its preparation followed the established principles of scientific assessments, similar to those applied for MAR1 and the IPCC, involving an open and rigorous process of author selection, external peer-review, and stakeholder consultation.

The preparation of this report was launched in April 2021 through an open call for self-nominations of authors. The outline was developed during a Scoping Meeting where experts and scientists were consulted alongside governmental representatives and stakeholders. The framework and outline were reviewed and approved by the MedECC Steering Committee. The authors were selected and approved by the MedECC Steering Committee based on their expertise, country and gender balance (60 authors from 15 countries). The Zero Order Draft (ZOD) of the report underwent internal review in March and April 2023. The MedECC Secretariat received 479 comments from 15 reviewers. The First Order Draft (FOD) of the report and draft SPM underwent external peer-review and broad consultation with governments, decision-makers and stakeholders in July-September 2023. As a result, 820 and 247 comments for the longer report and SPM were received respectively by 64 reviewers. The authors revised the draft SPM between October 2023 and March 2024, addressing all comments. The stakeholder consultation on the SPM was concluded through the online plenary consultation on April 29, 2024 during which the SPM was approved line by line. These included MAP Focal Points, Plan Bleu Focal Points, members of the Mediterranean Commission on Sustainable Development (MCSD), MAP Partners, as well as members, observers, and partners of the UfM Climate Change Expert Group (UfM CCEG) and the UfM Working Group on Environment and Climate Change (WG ENV-CC), among other MedECC partners.

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Interlinking climate change with the Water - Energy - Food - Ecosystems (WEFE) nexus in the Mediterranean Basin

Summary for Policymakers (SPM)

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Notes

• In the SPM, references for material contained in the full Special Report are given in curly brackets {}.

• **The SDG Index:** in the SPM, the Sustainable Development Goals (SDG) Index is used. This assesses each country's overall performance with regard to the 17 SDGs, giving equal weight to each goal. The score signifies a country's position between the worst possible outcome (score of 0) and the target (score of 100). The 2023 edition of the SDG Index includes 97 global indicators. Two-thirds of the data come from official statistics (typically United Nations custodian agencies) with one third from non-traditional statistics (e.g. derived from large-scale collection of passive data or remote sensing, produced by research centres, universities, and non-governmental organisations). Published since 2015, the SDG Index and dashboard has been peer-reviewed and the global edition was statistically audited by the European Commission in 2019. More detailed information is available on the website https://sdgtransformationcenter.org/.

• Each assessment finding is based on an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence.* The following terms have been used to indicate the assessed likelihood of an outcome or result: virtually certain (99–100% probability); very likely (90–100%); likely (66–100%); about as likely as not (33–66%); unlikely (0–33%); very unlikely (0–10%); and exceptionally unlikely (0–1%). Additional terms (extremely likely (95–100%); more likely than not (>50–100%); and extremely unlikely (0–5%) are also used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely.*

• In the SPM, the Special Report on Emissions Scenarios (SRES) defined in IPCC AR4 and Representative Concentration Pathways (RCP) defined in IPCC AR5 are cited. RCPs are greenhouse gas concentration trajectories (not emissions) used for the 5th phase of the Coupled Model Intercomparison Project (CMIP5) and labelled in line with a possible range of radiative forcing values in the year 2100: 2.6, 4.5, 6.0, and 8.5 W m^{-2} respectively. These correspond to one stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5). SRES scenarios are organised into four socio-economic families (A1, A2, B1 and B2), translated in terms of greenhouse gas and aerosol emissions. SRES scenario B1 is similar to RCP4.5, scenarios B2 and A1B1 are similar to RCP6.0, and scenario A2 is similar to RCP8.5. In the report, low-emissions scenario refers to RCP2.6, intermediate emissions scenarios refer to SRES scenario B1, B2, A1B1 or RCP4.5 and RCP6.0, and high-emissions scenario refers to SRES scenario A2 or RCP8.5.

Executive Summary: Water-Food-Energy- Ecosystems (WEFE) nexus in the Mediterranean

The Mediterranean Basin, cradle of an ancient cultural heritage, culinary traditions, indigenous knowledge of agricultural practices and biodiversity, is often referred to as a "climate change hotspot", as the regional projections of global climate change are exacerbated with higher rates than globally. It also has highly vulnerable specific critical resources (water, agriculture, etc.) and socio-economic elements (adaptive capacity, human population growth, etc.). Population and economic growth, agricultural intensification, urbanisation, high pollution levels in air, land, seawater, and freshwater, tourism and increasing resource demand and inequality, all increase the vulnerability of local communities, the impacts on human health and the level of insecurity for water, energy, food and ecosystems (WEFE). Resource overexploitation is contributing to their rapid depletion and consequent environmental degradation, putting the capacity of Mediterranean countries to reach the Sustainable Development Goals (SDGs) of the 2030 Agenda at risk. The unsustainability of WEFE elements is not only characterised by insecurity but also by large disparities across countries (North-South divide mainly) and across territories (rural and urban areas), and by the multiple interlinkages (nexus), including synergies and trade-offs, between the four WEFE nexus components.

Among the key challenges faced by Mediterranean countries are water scarcity issues and strong dependency on energy and food imports. Three main pathways for action are currently being implemented to promote synergies between water, energy, food and ecosystems: (1) implementation of innovative technological solutions often relying on renewable energy and enhanced efficiency; (2) ecosystem-based solutions, including agroecology and Nature-based Solutions (NbS) such as green infrastructure and wetlands restoration; and (3) social approaches to reduce or modify consumption patterns, such as promoting restrained consumption and sufficiency, and adoption of the Mediterranean diet.

However, despite these actions, the current situation is not satisfactory for these four components with regard to the expectations of the nexus approach, and shows a concept-to-implementation gap. This gap is due to (1) the lack of accessible and reliable data on key indicators and variables; (2) insufficient knowledge, understanding and awareness of nexus synergies and trade-offs; (3) insufficient incentives and investments; (4) higher costs of nexus approaches in the short term as compared to silo approaches; and (5) the lack of adequate governance, which include the lack of inter-sectoral and multi-level coordination.

Despite existing platforms for exchanging and consolidating know-how and experiences in the Mediterranean, actions and interventions need to be enhanced to build institutional capacities which include (1) a science-policy interface as one way of reinforcing coherence; (2) enhanced funding mechanisms; (3) intra-regional dialogue; (4) deliberative approaches; and (5) pilot nexus approaches through modelling and assessment for more coordinated WEFE actions in the Mediterranean.

A. Interconnected water, energy, food and ecosystem security challenges

A.1 Background for the assessment

A.1.1 All recent assessments of anthropogenic climate change for the Mediterranean Basin, including the IPCC AR6 and MedECC assessment reports, indicate ongoing warming, exceeding global average rates, of the atmosphere (+1.5°C above the pre-industrial level) and the sea (0.29°C–0.44°C per decade since the early 1980s), changes in rainfall distribution (10 to 30% drop on average) and continuous sea level rise (1.4±0.2 mm yr^{-1} during the 20^{th} century). The combination of observed and projected increases in climate hazards, coupled with high regional vulnerability and exposure, make the Mediterranean area a 'climate change hotspot' (*high confidence*) {1.2}. High temperatures cause direct damage to humans and ecosystems. Among the main risk factors identified in the Mediterranean are drought (meteorological, hydrological, agricultural, and socio-economic droughts), due to trends characterised by a widespread increase in evaporative demand resulting from temperature increase, and a decrease in precipitation, leading to an increase in the duration and intensity of meteorological and hydrological droughts {1.2}. Drier conditions and increasing water scarcity are significant threats to agriculture and ecosystems, and to a lesser extent energy, through hydropower and thermoelectric plants (*medium confidence*) {2.2.2}. At sea, the impacts of climate change include the increasing acidification of seawater likely reducing marine productivity, affecting species distribution and triggering local extinction, as well as the rise in mean sea level, which has already increased by 6 cm over the past 20 years (*high confidence*). It could reach between 40 cm for the lowest greenhouse gas emissions scenario and 100 cm for the highest emissions scenario by 2100[1], increasing the risk of coastal flooding (*high confidence*) {1.2}.

A.1.2 Greenhouse gas emissions in the Mediterranean Basin account for 6% of global emissions, equally distributed between northern and southern regions, corresponding to an equivalent proportion of the global population, with fossil energy accounting for 76% of the energy mix and significant variation between countries. The power production sector represents 30% of the total, while industry represents 14%, the building sector 16%, the transport sector 28%, and other sectors 12%, including industrial process emissions, indirect emissions (for nitrous oxide only), agriculture (agricultural soils, agricultural waste burning, enteric fermentation, manure management), and waste. Mediterranean countries have significant potential to mitigate climate change with high potential for renewable energy, particularly in the South and East. Adverse effects of climate change on thermo-electric production and hydropower, and to a lesser extent solar and wind energy production, should be accounted for to meet energy demand, expected to decrease in the north of the basin and increase in the Middle East and North African (MENA) countries {1.2}.

A.1.3 The Mediterranean Basin has a long history of adaptation to harsh environmental conditions, such as dry and hot climates, and often poor soils. This has resulted in landscapes and agricultural practices that have been developed over millennia of human presence in this region {1.2; 3.1}. These practices and associated knowledge have been substituted through industrialisation and lifestyle changes that have not been adapted to Mediterranean conditions, with impacts on WEFE components {2.1.1.2}.

A.2 Current status of the WEFE nexus in relation to the Sustainable Development Goals (SDGs)

Insecurity for all nexus components (water, energy, food, and ecosystems) is the rule rather than the exception in many countries of the Mediterranean Basin, and this has far-reaching implications in terms of sustainability. The region faces pressing challenges of water insecurity (e.g. water stress), energy insecurity (with heavy dependence on mostly imported fossil fuels), food insecurity (comprising the triple burden of nutrition) as well as ecosystem insecurity (e.g. fast rate of biodiversity loss, on land and in the ocean) (*Figure SPM1*). However, unsustainability in all WEFE components is not only characterised by insecurity, but also by the existence of large disparities between countries, as well as by the multiple interlinkages between the four nexus elements.

A.2.1 **Mediterranean countries are facing numerous interrelated challenges in terms of access to and availability of water, energy, food and fertile land, as well as with regard to how these elements depend on and potentially impact ecosystems.** Mediterranean countries face several challenges in their implementation of the 2030 Agenda for Sustainable Development and are not on track to achieve many Sustainable Development Goals (SDGs). This is particularly relevant for SDGs relating to WEFE components, such as food (SDG 2), water (SDG 6), energy (SDG 7), and ecosystems (SDGs 14 and 15). The Mediterranean region has a general SDG Index score of 73.5 but there are huge differences between the sub-regions; the SDG Index shows better performance in Western Europe and lower values in Eastern Europe and MENA countries. The SDG scores of Mediterranean countries in 2022

1 Refer to "Notes" for the explanations on the emission scenarios.

ranged from 81.1 in France (ranked 4th globally) to 59.3 in Syria (global rank: 126) {4.1}.

A.2.2 **Water insecurity originates from water scarcity due to droughts, flood-induced risk to infrastructure, degradation of water quality, and unequal access {1.2; 2.1.1.3}.** Water plays a critical role in maintaining healthy ecosystems, reducing global disease, empowering women, enhancing the welfare and productivity of populations, adapting to climate change, and fostering peace, acting as a vital connection between the climate system, human society and the environment. Achieving SDG 6 (clean water and sanitation) is therefore essential to attaining all other SDGs, which is of particular importance in the Mediterranean Basin {1.1}. **From the perspective of SDG 6, there are significant disparities between countries and most of the countries have significant challenges to address {4.1}**. Already, 180 million people suffer from water scarcity in the Mediterranean, but the quality of water is also decreasing with the increase in water salinity due to groundwater overexploitation and the presence of pollutants (e.g. nutrients and heavy metals) {1.2; 2.2; 2.3.1}. The key challenge for all MENA countries is water availability – due to frequent droughts leading to water scarcity and unsustainable use of limited water resources and overconsumption {4.1}. Challenges related to overexploitation of water resources and unsustainable water use leading to water shortages are due to a lack of sound water governance and in particular, of proper implementation of Integrated Water Resources Management (IWRM) {1.2}. Water shortage can lead to competition between sectors, including agriculture, industry, drinking water supply and tourism {1.2}. It can also lead to conflicts when combined with socio-political, economic, and environmental factors {2.3.1.3}.

A.2.3 **Food insecurity in the Mediterranean is significant and it is characterised by the triple burden of malnutrition: undernutrition, over-nutrition and hidden hunger.** The worst cases are found in North Africa, where all countries face major challenges. Achieving SDG2 (zero hunger) presents one of the most critical challenges of all WEFE components. Statistics on the prevalence £of undernourishment are not accessible for countries such as Palestine and Syria. None of the Mediterranean countries achieved the targets by 2020 and for all of them, either significant or major challenges remain, with disparities between countries {4.1}. High dependency on food imports, particularly for MENA countries, makes the region highly vulnerable to external uncertainties and variability outside the Mediterranean region. A dietary shift away from the traditional Mediterranean diet among the population, particularly children and adolescents, is mainly accompanied by increased malnutrition trends in the form of overweight and obesity, as well as degradation of ecosystems and greenhouse gas emissions (*high confidence*) {2.3.1.3; 3.2.6; 4.1}.

A.2.4 **The region faces challenges in securing its energy supply and matching demand.** For most Mediterranean countries, achieving SDG 7 (affordable and clean energy) is still a challenge despite variable progress over time in some of them. Access to electricity in urban areas is universal in most Mediterranean countries (i.e. 100% of the urban population has access to electricity). Access to electricity is lower in rural areas {4.1}. The challenge for nearly all Mediterranean countries, except Algeria, Egypt, and Libya, is their strong energy dependence on imports. Energy insecurity in the region is also increased by the existence of political conflicts between countries {4.1}. The share of electricity produced from oil, gas and coal sources ranges from less than 10% in France to more than 90% in Algeria, Croatia, Cyprus, Egypt, Israel, Jordan, Lebanon, Libya, Malta, Syria, and Tunisia. In general, Mediterranean countries are still highly dependent on fossil fuels to produce electricity {3.2; 4.1}. Renewable energy consumption only accounted for 11% of total energy consumption in 2020, about nine percentage points lower than the European Union (EU) and three percentage points lower than the global level {1.2}. Reducing energy demand, including increased energy efficiency and energy sufficiency, is necessary to reduce environmental degradation. It is also advantageous for the region to explore alternatives for ensuring energy security, particularly in light of the limited presence of established policies to reduce energy demand. Mediterranean countries have significant potential to mitigate climate change through an accelerated energy transition, including renewable energies deployment that requires effective land and sea use planning to avoid conflicts with other uses {1.2; 2.2.4}.

A.2.5 **Marine and terrestrial ecosystems are under acute pressure in the Mediterranean region.** Biodiversity loss, deforestation, wildfires, land use changes, and pollution are widely reported trends that are severely undermining Mediterranean ecosystems {1.2; 4.1}. Both marine and terrestrial ecosystems face significant challenges in the Mediterranean, where most countries are not on track to achieve SDGs 14 (life below water) and 15 (life on land). Forest degradation is expanding, and some polluting sectors are undergoing rapid growth, such as coastal mass tourism and land and maritime transport {1.2; 4.1}. With regard to marine ecosystems, unsustainable fishing, warmer temperatures, acidification and water pollution, including underwater noise, all reduce marine productivity, affect species distribution and trigger local extinctions {1.2}. Twelve Mediterranean countries still face major challenges with SDG 14, while seven others face significant challenges. The situation improves slightly with terrestrial ecosystems (SDG 15), but still, ten Mediterranean countries face significant challenges, whereas three countries face major challenges to achieve this SDG {4.1}.

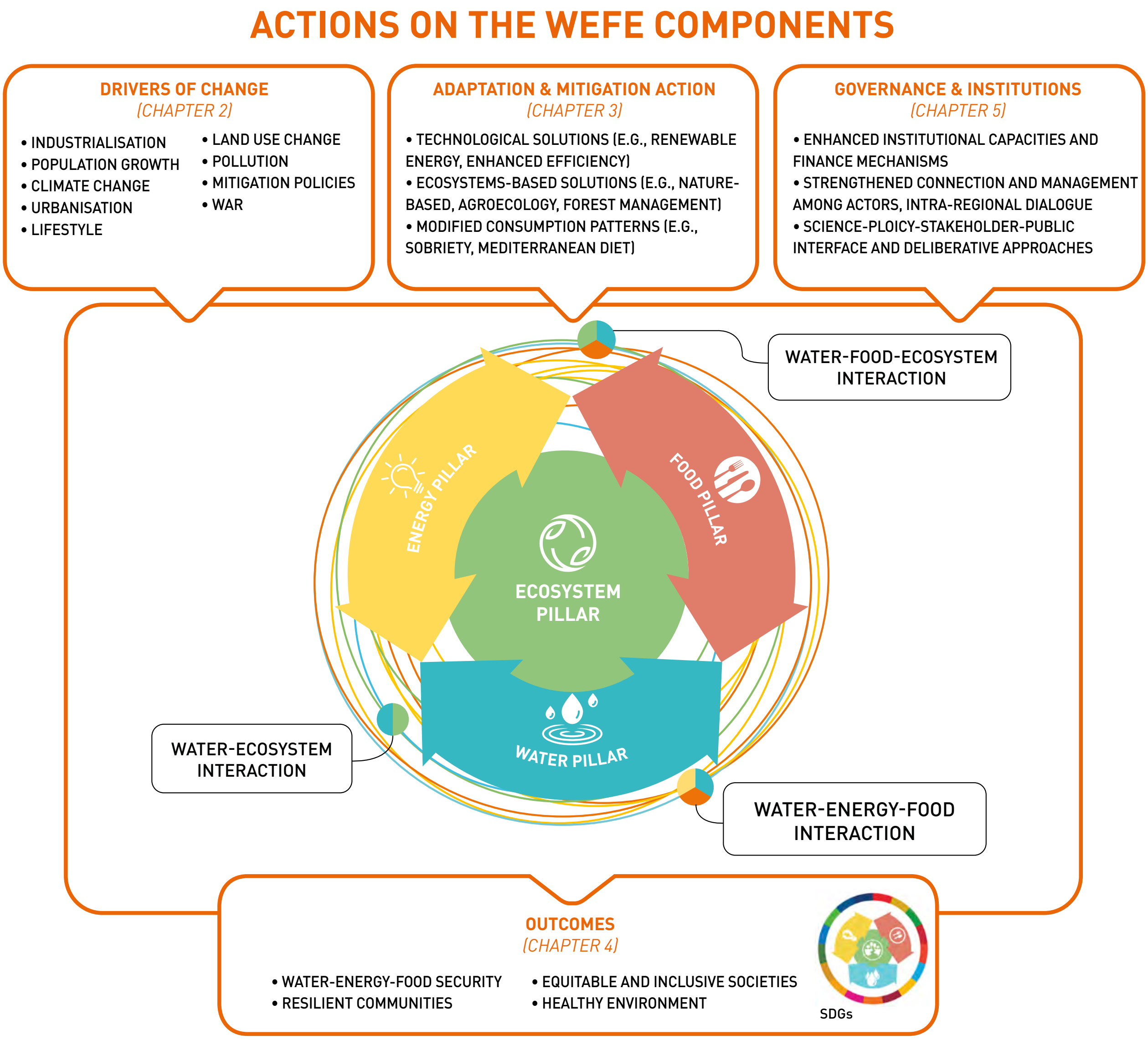


Figure SPM1 | Schematic of the WEFE concept and report outcome for the Mediterranean Basin.
A variety of direct and indirect drivers of change impact the WEFE components. WEFE has a series of two, three and higher level interactions that need to be addressed through appropriate governance and institutions capable of developing adaptation and mitigation actions that promote synergies to achieve water, food, energy security and ecosystem health in compliance with the SDGs.

A.3 Impact of the drivers of change on the WEFE nexus

WEFE challenges are amplified by current and future direct and indirect drivers of change that are external to the WEFE nexus, particularly climate change, pollution, land use changes, population growth, lifestyle changes, urbanisation, migration, industrialisation, and conjunctural crises such as pandemics and conflicts.

A.3.1 **Water security in the Mediterranean is affected by a combination of factors, including climate change, densely concentrated population growth, pollution, saltwater intrusion, land use practices, and unsustainable resource management, among others {1.2; 2.2.1}.** Future mean precipitation projections for the Mediterranean region foresee reductions of approximately 4% per 1°C global warming (*high confidence* for global warming levels above 2°C with a marginal projected increase in winter at the northern boundary of the northern Mediterranean) {1.2; 2.2.1.1}. Under a 2°C warming scenario, the frequency and duration of meteorological droughts are projected to increase in the southern Mediterranean countries, and the frequency of agricultural droughts is projected to be 150 to 200% more likely (*high confidence*) {2.2.1.1}. Population growth, economic development and lifestyle changes have led to increased water demand, resulting in water shortages and depletion of water resources (*high confidence*). The increasing levels of urbanisation, industrialisation, and unsustainable agricultural practices have led to a heightened need for water, which has resulted in unsustainable rates of water consumption {3.1; 3.2}. Inefficient irrigation methods are responsible for the squandering of water resources and the aggravation of water scarcity in the area {3.2} (*high confidence*). Moreover, unsustainable resource management has resulted in pollution of water resources and groundwater depletion {2.2.1.3}. In addition, inadequate land and resource management practices are also a contributing factor to water insecurity. The water-infiltration and water-holding capacity of soils can be adversely affected by activities such as deforestation, soil erosion, and improper land use practices, which can increase the likelihood of flash floods and reduce water quality {2.2.1}.

A.3.2 **Land and environmental degradation, pollution, land use changes, water scarcity, rural exodus and urbanisation, climate change, and dietary change lie behind the current levels of food insecurity in the Mediterranean {2.3.1}.** There are large disparities between regions, with a significant gap between the northern, southern and eastern Mediterranean. Population growth and conflict in some countries increase food insecurity. Climate change presents a significant threat to agricultural productivity, especially in arid and semi-arid regions. Decrease in crop yields, caused by reduced water availability and heat stress, is likely to affect staple crops such as olives, grapes, fruits, cereals, and vegetables. Levels of projected changes vary depending on countries, scenarios and crops, ranging from –80% for sunflowers in Spain and +26% for olives across the entire Mediterranean Basin (*medium confidence*). Agricultural land can be lost due to coastal water, soil salinisation and desertification {2.3.2}. The livestock sector is expected to suffer the negative effects of heat stress, limited feed resources, and deteriorating health and productivity. Climate change also impacts fisheries and aquaculture, resulting in the regional eradication of significant aquatic taxa {2.3.1.1} and modification of species distribution {1.2}. Furthermore, industrialisation and urbanisation have significantly transformed the Mediterranean agricultural sector. This transformation has been exacerbated by various factors, including a shift towards modern lifestyles, increased food demand and increased international trade. The region is subject to significant impacts from changes in land use {2.3.1}. Food security concerns in the region are further aggravated by the compounding challenges arising from conflicts such as the Russo-Ukrainian War, and the region's significant reliance on food imports. The potential consequences of disturbances in the food and fertiliser industries, in conjunction with the impacts of climate change, can be significant in terms of both the availability and accessibility of food {2.3.1.3}.

A.3.3 **The main drivers of change affecting energy production and demand are primarily not climate-related (population growth, lifestyle changes, industrialisation, and mitigation policy planning) {2.4.1}.** Climate change through increased temperatures marginally affects solar energy production (less than 2% decrease for global warming levels up to 3°C) (*low confidence*) {1.2; 2.4.1.1}. Regarding wind energy, projected wind speed decline affects wind energy production (up to 8% decrease for global warming levels of up to 3°C) (*low confidence*) {1.2}. Hydropower and thermo-electric production, including nuclear, is expected to decline due to decreased streamflow and increased water temperature, leading to a 10 to 15% decrease in thermopower by 2050 in the highest emissions scenario (*high confidence*) {1.2; 2.4.1.1}. Nuclear power plants situated along the coast are exposed to the potential impact of rising sea levels and flooding caused by extreme weather events. Quantification of global warming impacts on future energy demand is still highly uncertain but non-climatic drivers (e.g. population growth, urbanisation and modernisation) suggest a decrease of 10 to 23%e by 2040 compared to 2015 in the northern Mediterranean and an increase of 55 to 118% in 2040 compared to 2015 in the MENA countries {1.2; 2.4.1.2; 2.4.1.3; 2.4.1.4}.

A.3.4 **Climate change has major impacts on dryland ecosystems in the Mediterranean region, including vegetation productivity, biodiversity, and the stability and northward expansion of semi-arid regions.** The coupled effect of warming and drought increasing aridity is related to the decrease in the provision of several terrestrial ecosystem services such as soil conservation, water storing capacity, timber, mushrooms and food production, tourism and recreation, biodiversity and carbon storage. Furthermore, climate change increases the vulnerability of ecosystems towards diverse forms of disturbances, such as wildfires, pests, and diseases, etc. {2.5.1.1}.

A.3.5 Conjunctural drivers of change, such as recent conflicts and pandemics have suddenly negatively impacted the WEFE nexus and its hierarchical constituents, as well as the SDG indicators {4.1}.

B. Cascading impact of drivers of change through the nexus components

The change in WEFE components due to climatic and non-climatic drivers can affect the relevance of adaptation and mitigation measures at various temporal and spatial scales. The complex web of interactions between WEFE components can first result in cascading effects through which changes in one element from drivers of change result in changes in the other WEFE components, in turn generating multiple loops and feedback paths. Sustaining healthy ecosystems needs to be at the heart of interventions, since degraded ecosystems cannot provide their associated ecosystem services, hampering water, food and energy security.

B.1 Cascading from the water pillar (*Figure SPM2*)

B.1.1 The generally negative change in the water component causes an almost direct negative change in all food access and availability indicators as the water and food pillars are significantly correlated (*high confidence*) {2.2.2; 2.3.1.1}. Water scarcity reduces agricultural yields, and the agricultural sector, which is a significant water consumer in the region, is facing mounting challenges in obtaining adequate water resources for irrigation purposes {2.2.2; 2.3.1}. Actions seeking to increase water availability for irrigation using groundwater can lead to sea water intrusion and salinisation, reducing water quality and availability and further degrading ecosystems. The energy required to pump this water may contribute to greenhouse gas emissions and reduce energy available for other purposes. Actions seeking to increase water availability for irrigation using treated wastewater contribute to reducing pollution and can provide fertilisers that increase food availability, but compete with other energy uses {2.2.2}.

B.1.2 The projected declines in streamflow and increases in water temperature may lead to a strong decline in hydropower and thermoelectric power usable capacity in the Mediterranean (–2.5 to –7.0% for hydropower and from –10 to –15% for thermoelectric power in 2050s) (*high confidence*). The potential CO_2 emissions reduction from decreased use of nuclear (low-CO_2 emissions) or fossil fuel (large-CO_2 emissions) thermoelectric production depends on the technologies used {2.2.2; 2.4.1.1}.

B.1.3 Changes in the hydrological cycle and water quality due to pressure from climatic and non-climatic drivers significantly impact the structure and functioning of wetlands and riparian ecosystems, which are recognised as biodiversity hotspots in the Mediterranean (*high confidence*). These changes cause a loss of habitat for aquatic biota, rich and dynamic riparian plant communities, and waterbirds, and impact important migratory corridors and foraging hotspots. {2.2.2; 2.5.1.1}.

B.2 Cascading from the food pillar (*Figure SPM2*)

B.2.1 To address the impacts of the drivers of change on food security, actions aimed at increasing agricultural yield through business-as-usual responses linked to agricultural intensification and industrialisation can negatively impact ecosystem health through salinisation or changes in land use (*high confidence*) {2.3.2; 2.3.3}. Increased irrigation, as the main strategy for boosting crop productivity in the Mediterranean, can have a high cost in terms of water use and water pollution (e.g. nitrate leaching and salinization of over-exploited aquifers) (*high confidence*) {2.3.2.; 2.3.3; 3.2.2}. The contamination of water bodies by industrial and agricultural activities results in a decline in water quality, making it unfit for human consumption and detrimental to the well-being of ecosystems. Additionally, the projected increase in irrigation crop requirements under climate change scenarios can exacerbate existing competition for water resources between sectors (*medium confidence*) {2.3.2}. Industrialisation of agriculture leads to ecological deterioration, characterised by deforestation, amplified emissions of greenhouse gases, escalated energy consumption, and augmented water and fertiliser usage. The implementation of intensification techniques frequently results in agricultural land abandonment and a shift towards the cultivation of annual crops and monocultures, thereby affecting ecological sustainability and posing potential threats to biodiversity and agrobiodiversity. The decrease in agrobiodiversity poses an additional threat to the robustness of agricultural systems and traditional Mediterranean cuisine (*high confidence*) {2.3.1}.

B.2.2 Increased consumption of animal-based products due to population growth and lifestyle changes is responsible for an increase in greenhouse gas emissions and the disruption of local and regional nitrogen cycles, causing relevant impacts on ecosystem health (*high confidence*). Addressing this challenge by increasing unsustainable production and not targeting consumption behaviour leads to the same cascading effects as further agricultural industrialisation, with impacts on the water and ecosystems components {2.3.3}. The link with the energy component is the growing need for energy for food production, with further detrimental impacts if fossil fuels are the source of energy production, and increasing CO_2 emissions with decreasing adherence to the Mediterranean diet {2.3.2; 2.3.3}.

B.3 Cascading from the energy pillar (*Figure SPM2*)

B.3.1 Promotion of renewable energy to address the impacts of the drivers of change on the energy component can lead to land competition. The land requirements necessary in the Mediterranean region to fulfil 100% of current primary energy use are lower than 10% for hydropower, solar photovoltaics and wind, while for biomass, spatial requirements already exceed 100%. The spatial requirements for nuclear or natural gas never exceed 0.7%. With energy demand in MENA countries expected to double by 2040 compared to 2015, the fraction of land dedicated to energy production could reach over 10% of total land, with risks in terms of land degradation and biodiversity loss, while it could also conflict with food production and negatively impact food availability (*medium confidence*) {2.4.2}. Spatial planning and reduction in demand could help avoid these potential trade-offs.

B.3.2 Increasing energy production involves more water use. In Europe, water withdrawals for energy production are on average similar to those for agricultural irrigation {2.4.2}. In the MENA region, the share dedicated to irrigation is much higher (80%). However, this should be put into perspective with the water scarcity in these countries. Only a small fraction is consumed (6% for EU countries with large disparities between countries), the remainder being returned to the hydrological system. However, the energy sector remains an important part of withdrawals, negatively affecting water availability and competing for water with food {2.4.2}. Impacts on ecosystems due to excessive water withdrawals are also considerable. The Mediterranean region's dependence on power generation methods that require significant amounts of water, such as hydroelectric, thermal, and nuclear plants, therefore exposes it to the risk of reduced water availability and difficulties in managing water resources due to the effects of climate change.

B.3.3 Energy is a crucial input (upstream) in food processing and fertiliser production. If no changes are introduced to agricultural practices, the potential reduction in fertilisers will influence agricultural production by introducing lower yields into current

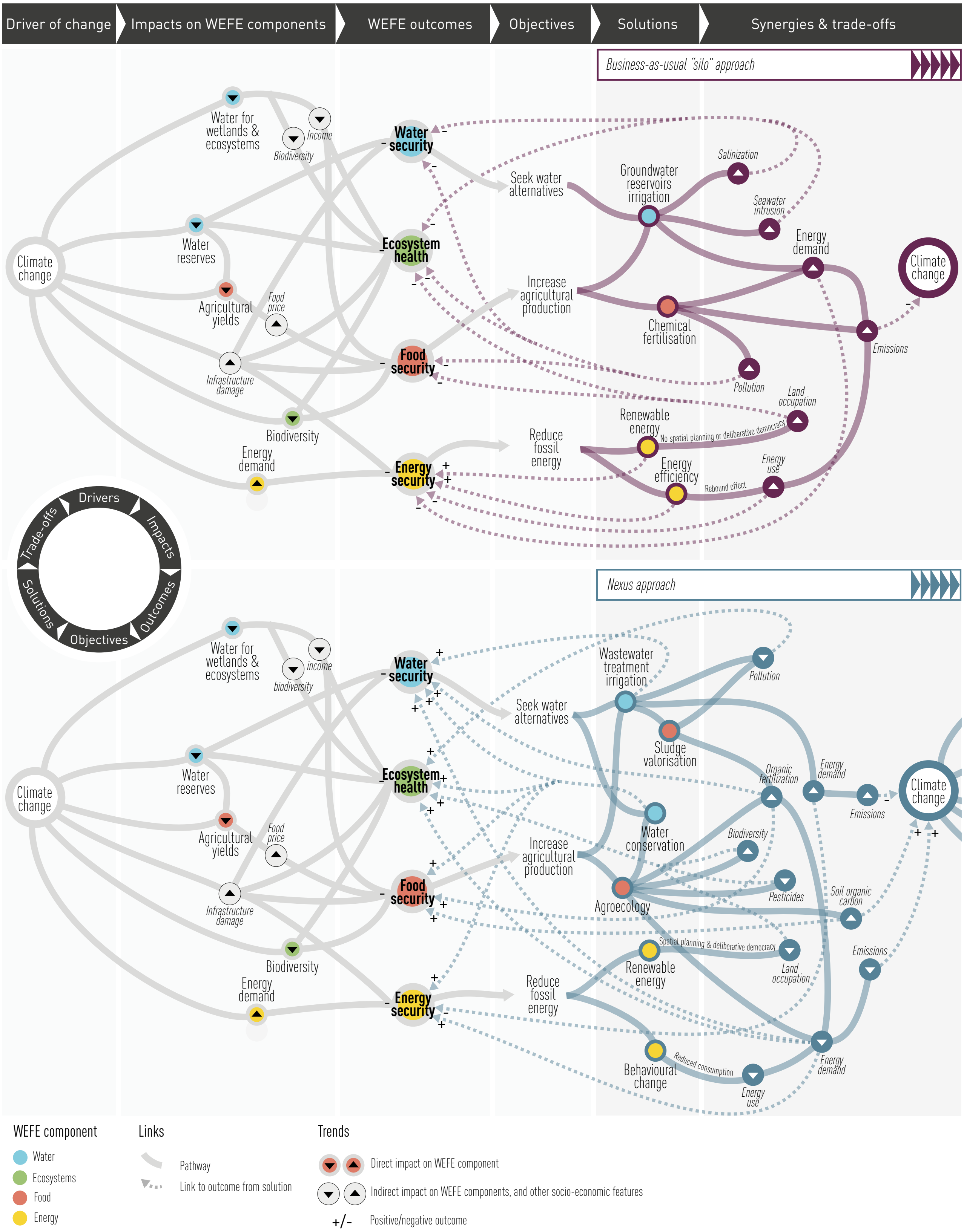


Figure SPM2 | Impacts, interactions and cascading effects on the WEFE outcomes of drivers of change and solutions. Climate change impacts the WEFE components. Policymakers need to find solutions to achieve water, food, energy security, and ecosystem health. Solutions developed following a silo-approach may reinforce the trade-offs, negatively impacting WEFE outcomes and increasing climate change. By integrating complexity, a nexus approach can significantly reduce impacts and promote positive WEFE outcomes.

monocropping agricultural systems. Consequently, a smaller quantity of farm products would be available to the food processing industry, leading to a reduction in market supply and a potential increase in prices {5.1.4}. Any increase in energy prices can also result in an increase in food prices, limiting access to food for the poorest populations.

B.4 Cascading from the ecosystem pillar (Figure SPM2)

B.4.1 The impact of climate change on ecosystem health can reduce the productivity of ecosystems and diversity at all levels, from intraspecific to landscape level. The degradation or depletion of ecosystems reduces the provisioning (water, food, biomass) and regulating (water quality, storm protection, carbon sequestration) ecosystem services provided by healthy ecosystems. In the case of water, climate and environmental changes combined with heightened concentrations of pollutants in aquatic environments could potentially result in a reduction in the quality of water, and a rise in sediment accumulation. Nevertheless, the effects are intricate and multifaceted, and not all ecosystems are affected equally. It is important to note that certain changes in climatic conditions may even lead to the enhancement of ecosystem services in specific instances {2.5.2}.

B.4.2 The reduction in biodiversity and degradation of ecosystems negatively affects the maintenance of soil structure and fertility, decomposition, remineralisation, and recycling processes, pollination, seed dispersal, and pest and disease control, which subsequently negatively impacts food availability {2.5.2}.

B.4.3 Changes in ecosystems, such as deforestation or alterations in water availability, may impact the accessibility and durability of energy resources, thereby causing potential impacts on the production and provision of renewable energy sources such as biomass and hydropower {2.5.2}.

B.5 Adaptation and mitigation solutions

Adaptation measures focusing on a single societal goal and one WEFE component can result in negative trade-offs, leading to maladaptation. In agricultural systems, this is partly due to adaptation pursuing a single goal, i.e. maximising short-term food production, which often means intensive agriculture, detrimental for soils and biodiversity. In the forestry sector, adaptation focusing on single societal goals, such as the spread of non-native tree species, can lead to higher fire risk (*medium confidence*). Integrated adaptation solutions are needed to address security issues, considering that mitigation consequences of the nexus approach can result from potential synergies and trade-offs derived from the interconnections between WEFE components.

B.5.1 A nexus approach to adaptation and mitigation actions promotes synergies between the WEFE components and minimises potential trade-offs. This is clear in the Mediterranean region as climate and environmental change negatively affects WEFE components both separately and through the cascading impacts of the drivers of change (*high confidence*). Silo approaches include poor and unsustainable irrigation practices leading to increased soil salinity and overall land degradation, or overexploitation of rangelands leading to soil erosion and land degradation (*high confidence*). Nexus approaches can include new irrigation techniques or returning to traditional ones, reuse of treated wastewater or desalinated water using renewable energy, agrivoltaics without land competition, or agroecological practices, such as agroforestry, intercropping and cover crops, which can reduce freshwater consumption, increase water conservation and reduce energy footprint while attempting to maximise local food production and protect ecosystems {3.2.1; 3.2.2}.

B.5.2 Adaptation and mitigation solutions are usually distinguished on a gradient of two main types: incremental and transformative ***(Figure SPM3)***. They include a variety of options, such as ecosystem-based approaches (including Nature-based Solutions, NbS), and technological and social innovation, including behavioural changes targeting consumption and lifestyle patterns, that can effectively address interrelated WEFE security issues and SDGs {3.2} ***(Figure SPM4)***. NbS include a set of actions inspired and supported by nature that simultaneously provide environmental, social and economic benefits, and help build resilience {3.2.2.1}. NbS strategies involve the implementation of blue and/or green infrastructure (e.g. green roofs and walls, urban grasslands and meadows, horticultural gardens, vegetated filter strips, swales, constructed and natural (or rewilded) wetlands and ponds). Early warning systems, climate services and risk management approaches have also shown broad applicability across various sectors in the Mediterranean and would benefit from incorporating an integrated nexus approach. Decision support tools, online platforms, and other products co-developed with users can provide information and services to support their decision-making {3.2.3.1}. Policies and actions that operate across the food system can have significant potential to adapt to climate change and reduce emissions, among other benefits (3.2.2; 3.2.3; *high confidence*). These involve promoting sustainable ecosystem and forest management that includes changes in agricultural and livestock systems to increase carbon storage in soils (e.g. agroecological approaches such as agroforestry or well-managed extensive livestock systems) and simultaneously targeting behavioural change, including reducing food loss and waste or influencing dietary choices (e.g. reducing overall meat consumption). They can thereby enable more sustainable land use management, enhance food security, reduce water use, water contamination and soil degradation, and promote biodiversity conservation.

B.5.3 There are a large variety of implemented solutions at various spatial scales, with uneven distribution across the whole Mediterranean basin ***(Figure SPM4).*** Social options based on behavioural change show the highest positive effect on all four pillars of the nexus, with a robust amount of evidence. In general, green options, such as Nature-based Solutions (NbS) and agroecological management practices, have positive impacts on the four pillars and are the most transformative ***(Figure SPM3),*** although further evidence is needed to assess specific NbS {3.2.3}. More evidence is required to assess the effect of adaptation options related to governance and institutions, in particular on policies for water pricing and limiting and reducing water use {5.1.4}. Some first attempts have shown solely positive effects on the four pillars. Options related to water use and management are the most complex and controversial, because they can have negative impacts on other pillars, but this negative effect seems low and requires better analysis {3.2.3}.

B.5.4 Drivers of change are evolving at a fast pace with strong impacts WEFE components, potentially jeopardising the resilience of already implemented actions {2.2.1, 2.3.1; 2.4.1; 2.5.1}. A modelling-based nexus assessment based on different climate, socio-economic and demographic change scenarios using different disciplines helps understand the resilience level of sustainable development options and avoid maladaptation and unanticipated effects {1.3.2; 3.3.2}. However, nexus modelling requires access to long-term series of data and open platforms {3.3.2}. It is therefore advisable to consider changes in system variables when designing integrated policies.

B.5.5 Transformative adaptation relies more on social innovation and requires increasing human inputs and system re-organisation, but it can be the most appropriate response to climate change and other drivers of change, when the severity of the expected impacts is particularly high or when current incremental adaptation options are reaching their limits in terms of implementation and functionality {3.1}. Adaptation and mitigation solutions can range from those more related to ecological and consumption-reducing behaviours to those more related to scientific and technological innovation {3.2}. Science and technology are part of the solution but require a broad understanding and societal engagement to achieve transformation through behavioural change. The varying levels of engagement of, and trust in, different stakeholders, including civil society, in the Mediterranean region, hampers the development of a nexus approach that demands a high level of cooperation and mutual trust {3.3}. Implementation of new technologies requires increasing participation and considering social concerns to avoid maladaptation.

B.5.6 Adoption and implementation of adaptation and mitigation measures can be undermined by various financial, scientific, geographic and institutional challenges. The implementation of solutions that take into account the nexus can be more cost-effective and cost-efficient than other solutions, however this requires considerable funds in the initial stages. Financing such approaches can be further hindered since WEFE programmes have many important socially oriented components that are typically of limited commercial value and potential {3.4.1}. Many northern Mediterranean countries are more likely and more financially ready to support such initiatives, whereas southern and eastern Mediterranean countries could require international support and commitment in the form of financial

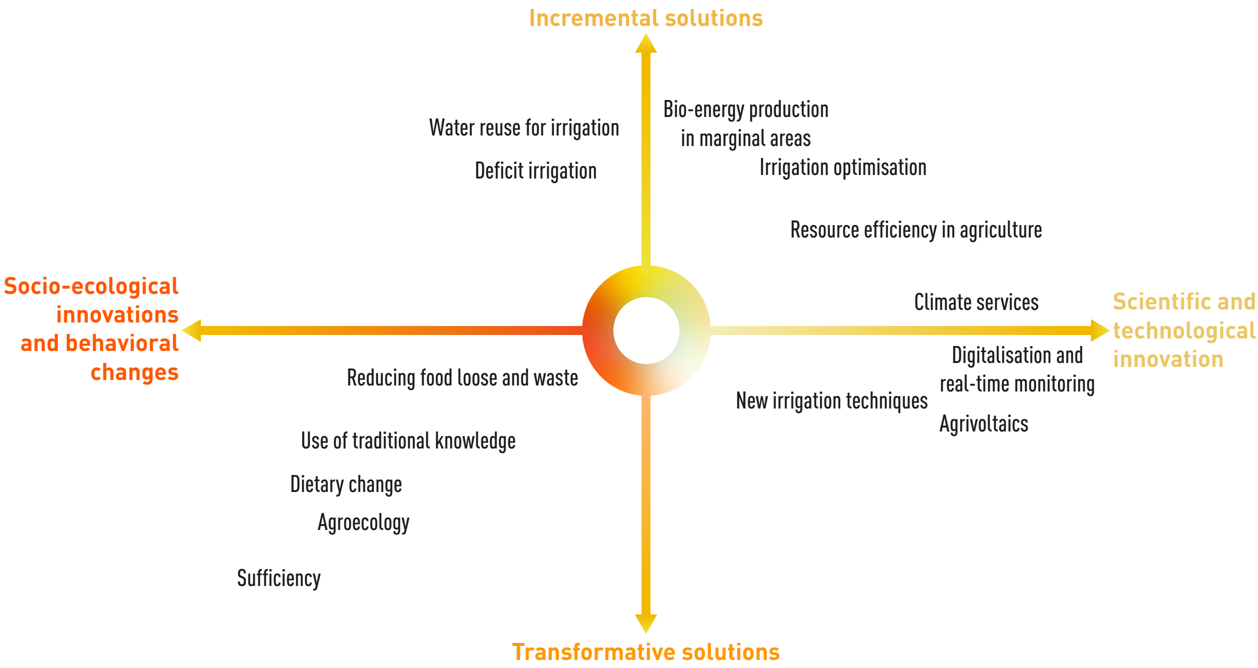


Figure SPM3 | Different gradients of possible adaptation and mitigation solutions for WEFE components used in the Mediterranean region. Adaptation and mitigation solutions range from incremental to transformative, and from scientific and technological innovation to socio-ecological innovations and behavioural change.

or scientific support to increase the adoption of the new approaches that will lead, in the long term, to the sustainability of the entire Mediterranean {3.4.4}. Indeed, technology implementation in southern countries still lacks adequate financing and appropriate policies {3.4.4}.

C. From the nexus concept to its implementation for sustainable development

C.1. Data, indicators and assessments

C.1.1 **Existing approaches used to tackle sustainability challenges in the WEFE sectors of the Mediterranean region have adopted fragmented planning and management frameworks that lack sufficient consideration of the intricate interconnections between these resource systems to address sustainability challenges in the Mediterranean (*high confidence*) {4.2}.** The WEFE nexus approach offers an integrated planning, cross-sectoral cooperation, and decision-making framework to analyse the interactions between the WEFE components in the Mediterranean region and identify trade-offs and co-benefits that might be overlooked in single-sector approaches (*high confidence*) {4.2}. The WEFE nexus approach better identifies potential synergies or conflicts between sector policies because it provides a framework in which the role of ecosystem services is more explicit. The sustainable use of ecosystems and conservation of biodiversity are essential pillars for successfully achieving sectoral development goals in the Mediterranean region {4.2}.

C.1.2 **The lack of complete and disaggregated data on the components of the WEFE nexus together with other issues related to data quality and accuracy, and the unwillingness of authorities to make certain types of required data available to researchers and other stakeholders are a major barrier to wider adoption and application of the WEFE nexus in the Mediterranean region {3.4; 4.2; 4.4}.** The complexity and multi-disciplinary nature of the nexus means that the models and methods to assess it and provide results for the full spectrum of its benefits need to cover many different scientific fields. In addition, data are not typically collected or available on a long-term basis, meaning that for

a

WEFE nexus adaptation and mitigation strategies	Existing management responses in the Mediterranean basin	Water pillar SDG 6		Energy pillar SDG 7		Food pillar SDG 2		Ecosystem pillar SDG 14 SDG 15	
Governance and Institutional	Policies on water pricing and limiting and reducing water use (3)	++	o	++	o	++	o	++	o
Technological options	Use of renewable energy in agricultural and other sectors (42)	+++	o	+++	-	+	-	+	-
	Early warning systems and climate services (7)	+++	o	+	o	+++	o	+	o
	Digitalisation and precision agriculture (2)	+++	-	+	o	++	o	+	o
	Increased bio-energy crop production in marginal areas (8)	++	-	+++	o	+	o	++	-
Water conservation and irrigation solutions	Unconventional water resources and improved use efficiency (12)	++	-	+	-	+	-	+	-
	New irrigation techniques (16)	++	--	+	--	+	o	+	o
	Water reuse for irrigation (11)	+++	o	+	-	++	-	+	o
Nature- and ecosystem- based approaches	Nature based solutions (10)	+++	-	+++	o	+	o	++	o
	Agroecological management practices (18)	+++	o	+++	o	+++	-	++	o
Social options: behavioural change	Mediterranean diet and restrained consumption (30)	+++	o	++	o	+++	o	+++	o

IMPACTS AND RISKS

+ Positive impacts on WEFE nexus pillars

- Risk or trade-off on WEFE nexus pillars

Limited

Medium

Robust

LEVEL OF AGREEMENT/CONFIDENCE

+++

b

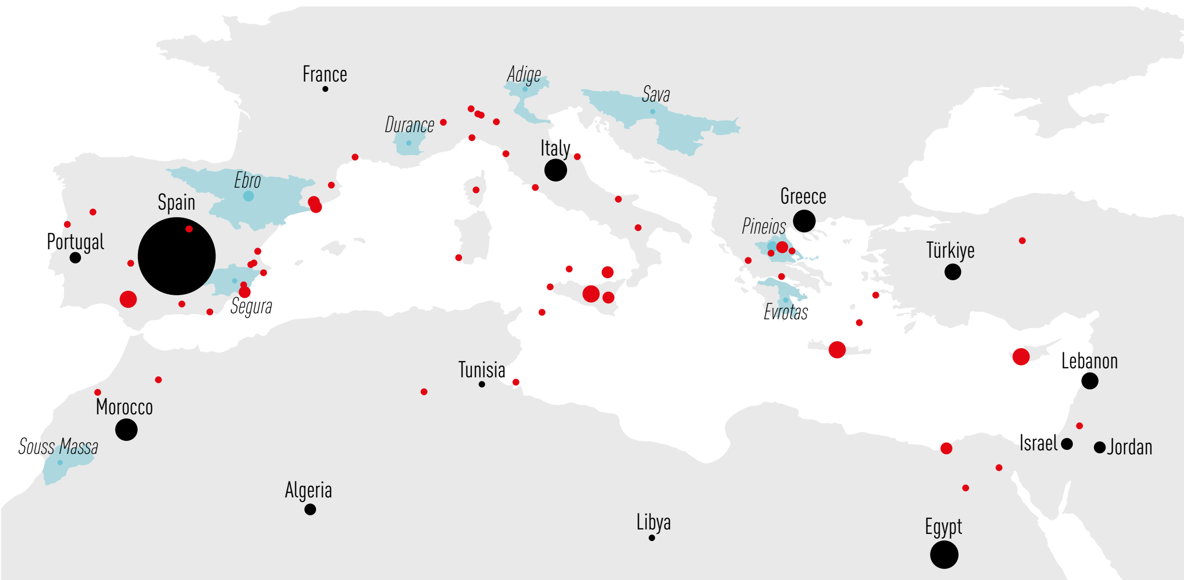


Figure SPM4 | (a) Assessment of the main impacts and trade-offs of the WEFE nexus adaptation and mitigation solutions implemented in the Mediterranean countries. The link is made to the SDGs through the nexus pillars. The numbers in brackets are the number of articles used for assessing each solution. The amount of evidence is quantified by the number of reviewed articles (given by numbers in brackets and categorised by limited in red, medium in orange and robust in green), while the degree of agreement measures the consensus between the articles (o for low agreement or limited evidence, + for low level of agreement/evidence, ++ for medium and +++ for high). This table does not review all possible solutions, but those implemented in the Mediterranean, reported in the scientific literature and assessed in the report. **(b) Spatial distribution of examined case studies.**

many cases, original data is necessary to showcase the benefits of WEFE approaches compared to other solutions {3.4.2}. Nevertheless, currently available data have been key to the creation of indicators for nexus indexes specific to the Mediterranean region. Monitoring tools and spatial indicators, generally related to multiple SDGs, have been developed to describe the national and local characteristics of food-water-energy-ecosystem interdependencies in the Mediterranean region, highlighting their high heterogeneity both within countries and between countries, and making it possible for Mediterranean countries to be ranked {4.3}.

C.2. Governance and stakeholder engagement

C.2.1 **Governance for the WEFE nexus requires strengthened connections and better management through coordination, integration, coherence, deliberation and collaboration between actors and their respective strategies and actions, rather than the creation of new institutions {5.2}.** To effectively utilise the WEFE nexus approach for sustainable development, key principles must be followed, including understanding the interconnections between resources within a system, developing new technologies for innovative solutions and roadmaps for their broad use throughout the region, facilitating social innovation and deliberative approaches, and ensuring coordination across sectors and stakeholders {4.2}. Deliberative processes that work well for: 1) values-driven dilemmas; 2) complex problems that require trade-offs; and 3) long-term issues that go beyond the short-term incentives of electoral cycles can contribute to WEFE nexus management {5.2.5}. WEFE governance is a polycentric system, with diverse and varying decision centres or actions within sectors, which requires identifying independent and overlapping key state and non-state actors – governments (acting through different ministries and public institutions), subnational (local and regional) authorities, civil society organisations, private sector, citizen groups, funders, multilateral and regional organisations (e.g. FAO, Plan Bleu, UfM, UNECE, etc.), national and international research institutions (AARINENA, CIHEAM, CMI, CNRS, , European Commission's Joint Research Centre, GWP-Med, IRD, etc.), and national and International Development Agencies (e.g. ENABEL, GIZ, USAID, SIDA, etc.) {5.2.1} ***(Figure SPM5).***

C.2.2 Policies aimed at achieving sustainable development goals require systemic approaches and flexible forms of governance (i.e. the removal of institutional, technical, regulatory and economic barriers), in order to facilitate interdependencies across sustainability challenges and favour holistic approaches {4.2}. A pioneer of the WEFE concept at policy level is the IWRM framework designed to improve water resources management {4.2.; 5.1.1.}. Involvement of stakeholders from the quadruple helix (public administrations, academia, private sector and civil society) in the development and implementation of nexus approaches is crucial to providing multiple perspectives, ensuring political legitimacy and promoting dialogue on the sustainability of WEFE components {4.2}. Deliberative democracy instruments, such as citizen assemblies, can increase the legitimacy of political decisions and actions, enhance trust, and provide useful information on people's preferences and what trade-offs they are ready to accept {5.2.5}. Involving intra-Mediterranean transnational collaboration is needed to face the climate emergency and promote equitable sharing of the risks and burdens associated with sustainable development {5.3.3}.

C.3 The concept-to-implementation gap

A concept-to-implementation gap has been identified in the Mediterranean context, meaning that the current situation is not satisfactory for the WEFE nexus with regard to nexus approach expectations.

C.3.1 **Political and social conditions within Mediterranean countries involve varying levels of WEFE nexus policy implementation.** The practical implementation of WEFE nexus policies has been limited and lacks coordination among the different levels of managing authorities, between sectoral departments, political actors, and stakeholders. EU countries have a common policy framework, which is not the case for MENA countries. Most policy initiatives on the WEFE nexus in Mediterranean countries have focused on assessments and analyses, reaffirming the importance of the concept. However, the implementation of such an approach is still lacking, and several measures are still designed in "silos" {5.1.1; 4.3} ***(Figure SPM5).*** Disjointed legal frameworks, marked by diverse and frequently conflicting laws, particularly in relation to transboundary resources, can be seen on both sides of the Mediterranean

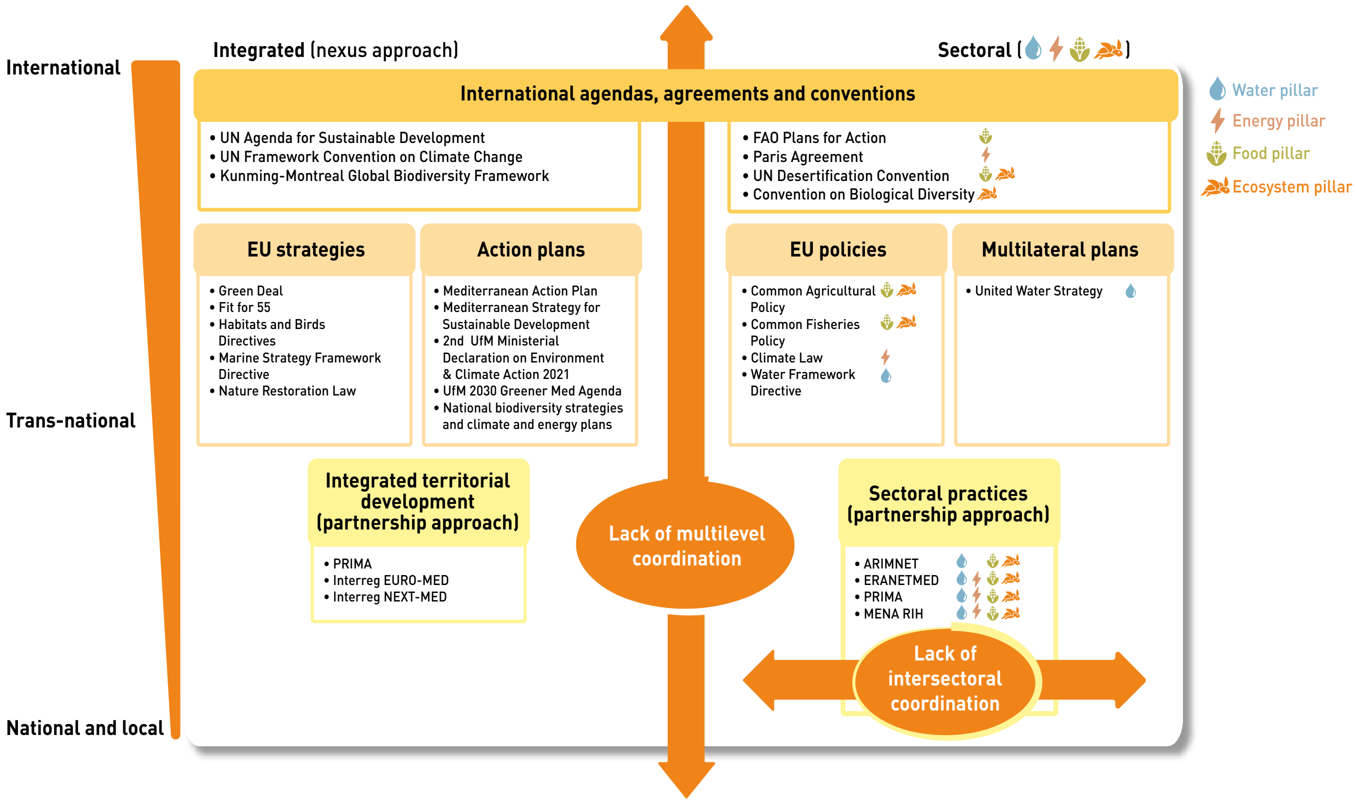
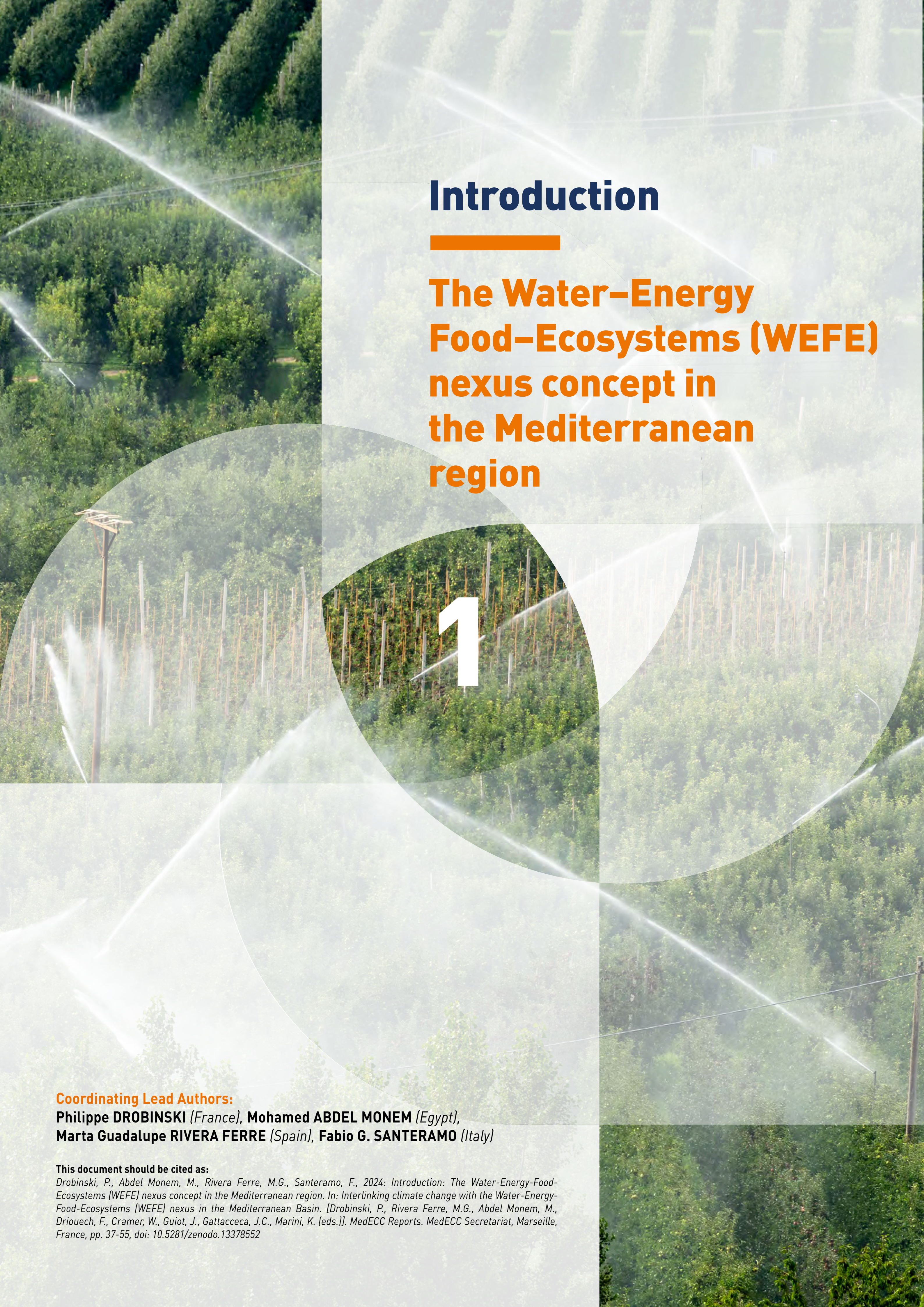


Figure SPM5 | Multi-level integrated and sectoral policies on the WEFE nexus in the Mediterranean (see {5.3.1; 5.3.3} for AIMNET, ERANETMED, MENA RIH and PRIMA programmes description).

Basin. When deciding on policies to implement, it is therefore beneficial to thoughtfully consider potential cross-sectoral implications {5.1.1; 5.1.3}.

C.3.2 **The limited effective implementation of WEFE nexus approaches in the region is attributed to an insufficient understanding of nexus trade-offs within science-policy-stakeholder interactions, to insufficient incentives {4.4}, limited vision, knowledge, development and investment, as well as the lack of solid empirical evidence regarding the potential benefits of a WEFE nexus approach {4.2}.** Universities and research organisations serve as knowledge generators and brokers, and could integrate nexus thinking and organise policy dialogue into their research agendas and curricula {5.2.3}. Another key challenge is related to the costs of nexus approaches, which may be higher in the short term than those of silo approaches, due to the information, expertise, time, coordination and financial resources required {4.2}.

C.3.3 **A series of actions and interventions are needed to build institutional capacities; enhance funding mechanisms; support intra-regional dialogue between implementers of the nexus approach, policymakers, and the general public; and pilot nexus approaches through modelling and assessment {5.3}.** Public-private partnerships are considered effective for funding the WEFE nexus and improving capacity building and awareness of involved partners {5.3.3}. Approaches that integrate both environmental sustainability and considerations of local, regional and global governance, together with economic factors, are more likely to succeed in achieving real-world applicability {4.2}. WEFE nexus governance should promote transparency, participation, and accountability through dialogue and cooperation among Mediterranean countries, supplemented by collaboration with international organisations and deliberative processes involving citizens {5.1.1; 5.1.2; 5.1.5; 5.2.5} ***(Figure SPM5).***



Introduction

The Water–Energy Food–Ecosystems (WEFE) nexus concept in the Mediterranean region

1

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Chapter 1

Introduction: The Water-Energy-Food-Ecosystems (WEFE) nexus concept in the Mediterranean region

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Executive Summary

In the intricate web of interconnected social, economic, and ecological systems, the relationships between water, food, energy, and ecosystems stand as undeniable pillars. These essential resources are under strong pressure from both direct and indirect drivers, including climate change, pollution, population growth, unsustainable consumption and production patterns, rapid urbanisation and unsustainable natural resource management, negatively impacting the livelihoods of millions throughout the Mediterranean and hindering progress towards the Sustainable Development Goals (SDGs). The effects of these pressures on resources are far-reaching, with adverse effects on communities and economies only partially mitigated by external resource imports.

The Mediterranean Basin is recognised as a "hotspot" for both climate change and water scarcity. Over the past fifty years, per capita water resources have significantly diminished, especially in the eastern and southern Mediterranean regions. This scarcity is compounded by existing conflicts, economic vulnerabilities, and social disparities.

The Water-Energy-Food-Ecosystem (WEFE) nexus approach aims to increase security in these vital domains, without compromising ecosystem health. Through the analysis of connections and interactions between these components, the WEFE approach seeks to optimise synergies and manage trade-offs between different technical and strategic responses. The nexus concept is applicable across various scales, ranging from local to global-regional contexts, allowing for comprehensive management strategies. At regional scales, water, energy and food security include imports and exports.

There is a growing need for transformation, and a paradigm shift in consumption and production patterns alongside changes in governance. Adopting the WEFE nexus approach involves moving away from fragmented sectoral development interventions towards integrated natural resource management and use. It presents opportunities to transform agrifood towards sustainability and contributes to fostering peace, as well as resilience and security for both humanity and ecosystems. Integrating the WEFE nexus into national policies and development plans emerges as a way to support SDG implementation, aligning with the interconnected nature of these global objectives. With its components present in 14 out of the 17 SDGs, the WEFE nexus emerges as highly relevant in the pursuit of these goals. In summary, there is a need to adopt a comprehensive and integrated approach to address the multifaceted challenges posed by resource pressures, climate change, and sustainable development in the Mediterranean region.

1.1 The nexus concept: from sectoral to systemic thinking

Water, energy, ecosystems and particularly food are essential resources required to meet human needs, and are inextricably linked through complex interactions (Salam et al., 2017; Zhang & Vesselinov, 2017). For instance, water and energy are essential inputs for food production. Similarly, water can be used for cooling and/or hydropower generation, while agriculture can produce biofuel crops and contribute to ecosystem degradation. Also, energy is needed to pump, treat and transport water. The interdependent relationships between these components have been highlighted as a web of complex relations and named the Water–Energy–Food (WEF) nexus (Dupar & Oates, 2012; Hoff, 2011; White et al., 2018). The term has strong implications for ecosystems, thereby extending the nexus concept to WEFE. *Figure 1.1* shows the WEFE nexus framework and describes its complexity. It illustrates the interdependencies with the lines surrounding the four nexus components. Each line represents a specific component, and when two lines cross, it identifies the interactions between the two associated components. More than two crossings, up to four, can occur, showing that the interactions do not necessarily go two–by–two but can also involve all nexus components.

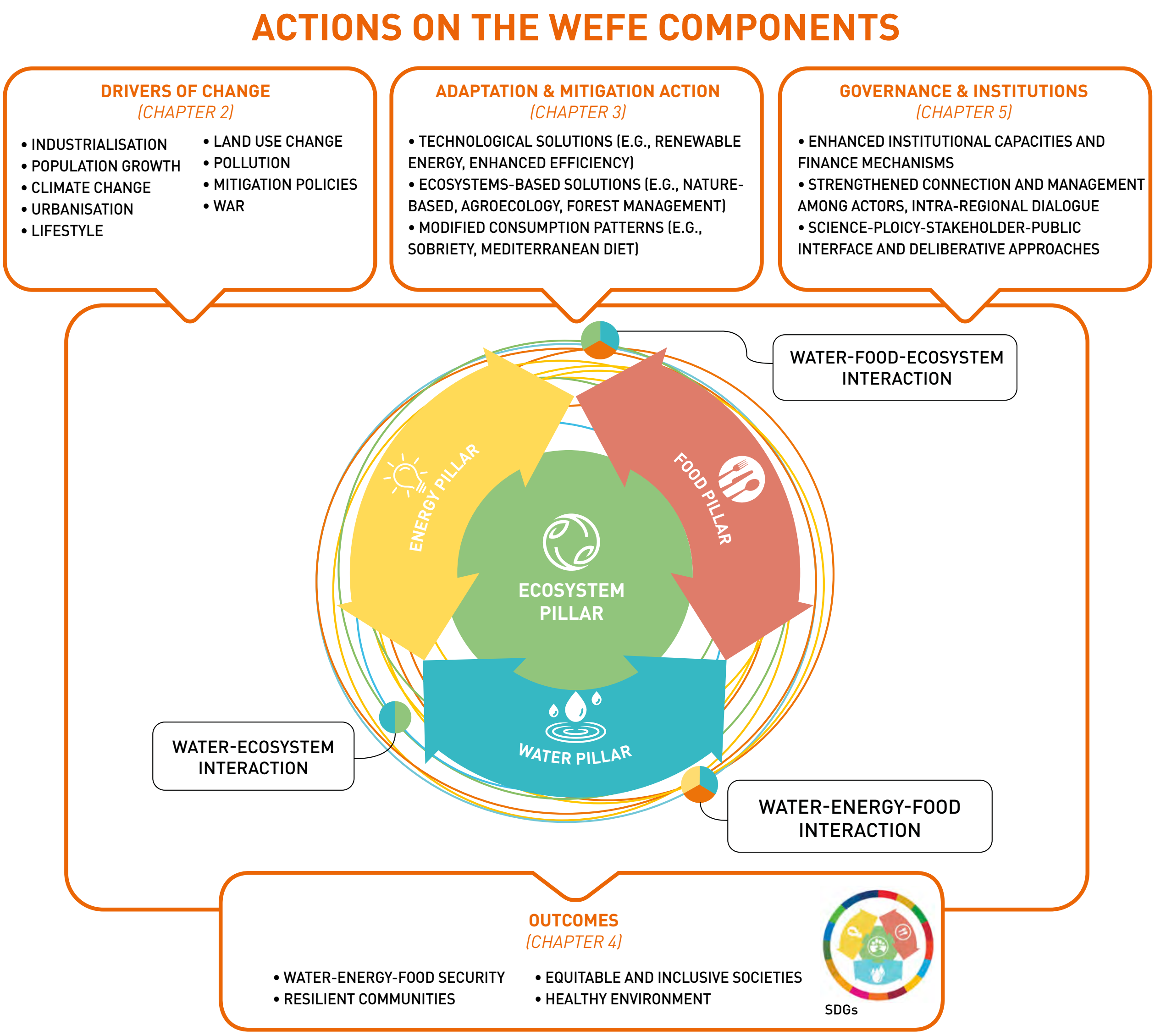

Figure 1.1 | Schematic of the WEFE concept.
WEFE components in the circle, with some examples of two-way interactions between them. Ecosystems are at the centre to highlight that all the other components depend on healthy ecosystems. Outer boxes refer to direct and indirect drivers of change impacting the WEFE governance and institutions action and outcomes achieved by implementing a nexus approach.

Figure 1.1 identifies the drivers of change that impact the nexus components, as well as the implemented actions in the Mediterranean Basin in terms of adaptation and mitigation. Adapted governance and specific institutional actions are essential to support the implementation of a WEFE nexus approach in the Mediterranean. The expected outcome of the nexus approach to address the sustainable development challenge in the Mediterranean Basin.

The formalised concept of cross-sectoral interlinkages, referred to as a "nexus", emerged in the 1980s, and gained prominence through the United Nations University's (UNU's) Food-Energy Nexus Programme, the World Summit on Sustainable Development, and the Bonn 2011 Nexus Conference, promoting systems integration, stakeholder engagement, and development pathway exploration (Estoque, 2023).

Like the nexus, the Sustainable Development Goals (SDGs) are defined as closely interlinked, but they are also key to the WEFE nexus approach. Over time, the nexus approach has been through various phases of development, resulting in more complex and diverse nexuses, whose components can be resource sectors/systems and/or specific socio-ecological issues (Estoque, 2023), and go as far as potentially covering all SDGs. However, the SDGs are today far from the target levels, as synergies and trade-offs were not considered in setting up the SDGs (UN, 2023a). SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy) and SDG 2 (zero hunger), but also SDG 13 (climate action), SDG 14 (life below water) and SDG 15 (life on land) in particular, are not only connected to each other but are also key to the WEFE nexus approach. Water plays a critical role in maintaining healthy ecosystems, reducing global disease, empowering women, enhancing the welfare and productivity of populations, adapting to climate change, and fostering peace, acting as a vital connection between the climate system, human society and the environment. Therefore, reaching SDG 6, of particular importance in the Mediterranean Basin, is essential to achieving all other SDGs (UN, 2023b). There is still no consensus with regards to the key nexus components that could potentially cover all the SDGs.

The main aim of the WEFE nexus is to analyse and communicate implications that consider the processes of producing, distributing, and consuming WEFE resources into a decision-making process and to manage them more effectively and efficiently (Abulibdeh & Zaidan, 2020). It means avoiding fragmentation in decision-making, recognising trade-offs and synergies across sectors, promoting improved governance across sectors, temporal scales and regions, and adopting integrated nexus thinking among policymakers. Sectoral policies need to be designed in a coordinated and integrated manner (Laspidou et al., 2020), including different geographical scales (Abulibdeh & Zaidan, 2020). An integrated nexus approach may ensure complementarities and synergies across sectors and help managing trade-offs and synergies in food, agriculture, water, energy, and ecosystems (Bizikova et al., 2013; Pittock et al., 2013) and reduces the risks of sectoral SDG (Nath & Behera, 2011). Some key benefits arising from using the WEFE nexus are for instance (1) exploiting co-benefits to improve overall performance by increasing resource use efficiency, changing waste into resources and fostering alternative practices to fulfil multi-sectoral needs; (2) streamlining development and improving resilience through benefits from healthy ecosystems, poverty alleviation and climate change mitigation and adaptation and (3) stimulating policy coherence and investments through collaboration between sectors and associated institutions (Adamovic et al., 2019). At regional scale, water, energy and food security also depends on how much is imported or exported (e.g. Allan, 2003; Jain et al., 2023) and a nexus approach makes it possible to understand the telecoupling effects of such dependency.

1.2 The sectoral analysis of water, energy, food resources and ecosystems from the MedECC First Mediterranean Assessment Report (MAR1) and IPCC Sixth Assessment Report (AR6)

An extensive review of the drivers of climate and environmental change and their impacts on water, energy, food and ecosystems was conducted in the MedECC First Mediterranean Assessment Report (MAR1) published in 2020 (MedECC, 2020a) supplemented recently by a dedicated chapter in the IPCC sixth Assessment Report (AR6) published in 2022 (Ali et al., 2022). Drivers of change including both ecological (direct) drivers like climate change, pollution, land and sea use change and non-indigenous species (*Figure 1.2*) as well as social, cultural, economic, political and technological (indirect) drivers of change, like industrialisation, demography, war, consumption behaviours (e.g. diet, travel, energy consumption), increase pressure on resources. However, MAR1 addressed water, energy, food resources and ecosystems in silos but not the interlinkages between them. All the information provided in this section can be found in the MAR1 (MedECC, 2020) and AR6 (Ali et al., 2022).

The Mediterranean Basin is considered to be a major "hotspot" of climate change with paradoxical behaviour in the water cycle (Ali et al., 2022; Fader et al., 2020). Virtually all continental and marine sub-regions of the Mediterranean Basin are impacted by recent anthropogenic changes in the environment (Lange et al., 2020). Due to anthropogenic emissions of greenhouse gases (GHGs), the rate of climate change in the Mediterranean Basin, including land and sea, is greater than global trends. Indeed, when the globe warmed by 1°C compared to the pre-industrial level, the Mediterranean Basin (land and sea) warmed by 1.5°C, greatly exceeding 2°C in summer. Warming could additionally increase between 0.5°C and 6.5°C by 2100 depending on the climate change mitigation scenario. Only the lower limit is compatible with the 2015 Paris Agreement (Ali et al., 2022; Cherif et al., 2020). At sea, the consequences are the increasing acidification of seawater and the rise in mean sea level, which has already increased by 6 cm over the past 20 years. It could reach between 40 and 100 cm by 2100 depending on the emissions scenario[1]. (Le Cozannet et al., 2019; Thiéblemont et al., 2019), and possibly more than one metre, increasing the risk of coastal flooding (Ali et al., 2022). The sea surface temperature has warmed by about 0.3°C -0.45°C per decade (depending on the sub-basin) and is expected to warm by 1°C to 4°C depending on the scenario. The absorption of CO_2 by the sea results in sea water acidification, adding pressure on ecosystems. On land, the duration and maximum temperatures of heatwaves will intensify, and summer precipitation is likely to drop by 10 to 30% in some regions[2].

Water sector: Temperature increase and water cycle change cause a wide range of impacts on human health (Linares et al., 2020) and result in increased water shortages and desertification (Fader et al., 2020). The per capita availability of renewable water resources declined between 1962 and 2017 by 78% for the Eastern Mediterranean and 68% for the Southern Mediterranean (FAO, 2022). With the reduction in runoff and aquifer recharge together with a higher use pressure, water scarcity[3] is expected, especially in the southern and eastern regions, which already experience low resources. Groundwater resources are not only subject to pressures resulting from unequal distribution, overexploitation, and accessibility, but also quality issues. Agricultural activities, leakage of wastewater from urban areas, or saltwater intrusion are the main sources of groundwater pollution, which can make the resource unusable (Fader et al., 2020). Challenges related to overexploitation of water resources, unsustainable water use and water shortages, are due to a lack of sound water governance and in particular right implementation of Integrated Water Resources Management (IWRM) (Fader et al., 2020; Vafeidis et al., 2020)[4]. Already, 180 million people suffer from water scarcity in the Mediterranean, but the water quality is also deteriorating with increase of water salinity due to groundwater overexploitation. As a result of the general scarcity of water resources, conflicts arise in different water use sectors (agriculture, tourism, industry, domestic use, as well as biodiversity conservation). In southern and

1 Four trajectories of emissions and concentrations of greenhouse gases, ozone and aerosols, as well as land use called RCP ("Representative Concentration Pathways") used for the 5th phase of the Coupled Model Intercomparison Project (CMIP5).

2 Precipitation is projected to decrease by approximately 4% per 1°C global warming with high confidence for global warming levels above 2°C. A marginal increase is projected in winter at the northern boundary of the northern Mediterranean Basin (Ali et al., 2022).

3 Water scarcity and drought are related but distinct concepts, and both can have significant impacts on the Mediterranean region. Water scarcity has been defined by FAO (2012) as a gap between available supply and expressed demand for freshwater in a specified domain, under prevailing institutional arrangements and infrastructural conditions. It is a chronic condition that occurs when the renewable freshwater resources are insufficient to meet the needs of people and ecosystems. It can be caused by various factors, including population growth, inadequate water management, climate change, and inefficient water use practices. On the other hand, drought is a type of extreme climate that is characterised by prolonged dry weather conditions, which disrupts the hydrological balance (EDO, 2023). It is a natural and temporary phenomenon that arises when an area experiences significantly less rainfall than usual for an extended duration, resulting in water shortages. Drought conditions are associated with a lack of precipitation, soil moisture deficit, and low water reservoir storage, which impacts a wide range of sectors. It is important to distinguish drought from aridity, which is a long-term climatic feature, and water scarcity, which is a situation where the available water resources are insufficient to meet water demand.

4 In the context of the Mediterranean Basin, Integrated Water Resources Management (IWRM) may include Integrated Coastal Zone Management (ICZM) and a source-to-sea approach to address water resources management as a comprehensive network linking land, water, delta, estuary, coast, nearshore and ocean ecosystems holistically supported by specific mechanisms and measures such as the sustainable blue economy (Michels-Brito et al., 2023).

eastern countries, agricultural use reaches 76–79%. In the northern countries, the four sectors are much more balanced (18–36%). Water shortage will lead to more and more conflicts among users and sectors, in particular agriculture and tourism, as the needs of these sectors peak in summer, especially in the Middle East and North African (MENA) countries as well as in Spain, where agriculture is the largest consumer of water (Burak & Margat, 2016; Mrabet et al., 2020) accounting for nearly 85% of water uses (FAO, 2022). As a consequence, demand for irrigation is expected to increase by 4–18% by 2100. Meanwhile other needs from demographic change, particularly the growth of large urban centres, could increase this demand by 22–74% (MedECC, 2020b). Conversely, more heavy rains and therefore flooding and significant soil loss due to erosion are projected during other seasons. The vulnerability of the Mediterranean population may thus increase with higher probability of occurrence of events conducive to floods as well as longer and more severe droughts (meteorological, hydrological, agricultural and socio-economic droughts – Fader et al., 2020) caused by evaporative demand, temperature increase and precipitation decrease (Drobinski et al., 2020b).

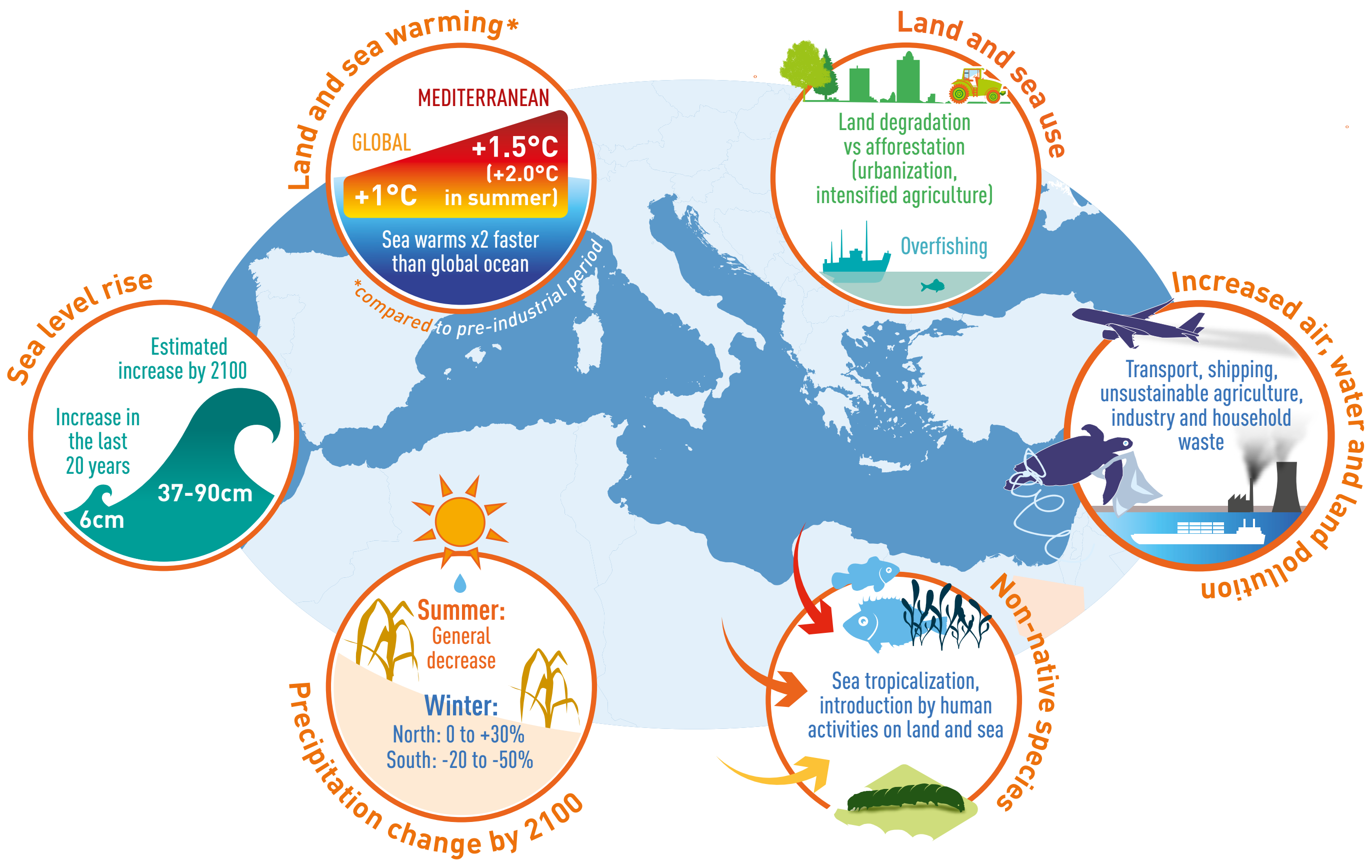

Figure 1.2 | Main drivers of environmental change in the Mediterranean Basin.
This infographic represents the key messages on climate and non-climate drivers of environmental changes in the Mediterranean Basin, based on Chapter 2 of the First Mediterranean Assessment Report (MAR1) (MedECC, 2020a)[5].

5 https://www.medecc.org/outputs/infographic-mar1-drivers-2022/

Food sector: Food production in the Mediterranean Basin is impacted by climate change in combination with land degradation, overfishing, sea level rise, and salinisation of coastal soils. Crop yield reductions are projected for the next decades in most current areas of production and for most crops (5% to 22% yield reduction for maize and wheat by the end of the 21st century without adaptation measures in the highest emissions scenario) (Mrabet et al., 2020). The cultivation of some crops with high water demand like maize or vegetables may even become impossible in many Mediterranean regions without enough water for irrigation (Mrabet et al., 2020). This may potentially be worsened by emerging plant and animal pests and pathogens, and perturbations in global food markets due to environmental crises elsewhere as most Mediterranean countries are net importers of cereals and fodder/feeding products. Climate change mitigation through innovative agricultural management practices, which can enhance agricultural systems resilience, can be implemented through a combination of carbon sequestration techniques, water-efficient strategies, and agroecological approaches (IPCC, 2019).

Ecosystems: Climate change and non-climatic factors are causing the invasion of non-indigenous species, impacting ecosystems and biodiversity. These non-native marine and terrestrial species are invasive, affecting sectors like fishing, agriculture, tourism, and resource scarcity (Balzan et al., 2020). Air pollution is increasing mainly due to land transport and maritime activity, with high temperatures increasing the effects of this pollution on ecosystem health. Land ecosystems are also vulnerable to increased risk of wildfires due to more favourable climate conditions (Balzan et al., 2020). Marine pollution, which can provoke outbreaks of jellyfish, mucilage and algal blooms, comes from agricultural, industrial and household waste, including plastics. Unsustainable fishing, adding to the already observed decline of fish landings of 28% from 1994 to 2017, warmer temperatures, acidification and water pollution, including underwater noise, will likely reduce marine productivity, affect species distribution and trigger local extinction of more than 20% of exploited fish and marine invertebrates around 2050 (Balzan et al., 2020; Moretti & Affatati, 2023).

Energy sector: The Mediterranean Basin's greenhouse gas emissions are 6% of global emissions, equally distributed between Northern and Southern Mediterranean countries, with fossil energy accounting for 76% of the energy mix with large variation between countries (Crippa et al., 2019; Drobinski et al., 2020a). The power production sector represents 30% of the total, while industry represents 14%, the building sector 16%, the transport sector 28% and other sectors 12% (Crippa et al., 2019). Renewable energy consumption accounts for only 11% of the total energy consumption in the region, about nine percentage points lower than the European Union and three percentage points lower than the global level (Bartoletto, 2021), while the Mediterranean countries have significant potential to mitigate climate change through an accelerated energy transition (Drobinski et al., 2020a).The Mediterranean Basin's potential for renewable energy, particularly in the South and East, must be capitalised on to meet the Paris Agreement (Drobinski et al., 2020a). Adverse effects of climate change on thermo-electric production and hydropower (down -20% for global warming levels up to 3°C) and to a lesser extent solar (less than 2% decrease for global warming levels up to 3°C due to the temperature effect on solar photovoltaic (PV) cell efficiency and wind energy production (less than 8% decrease for global warming levels up to 3°C due to wind resource decline and temperature effect on efficiency) (Drobinski et al., 2020a). should be accounted for to meet the energy demand, expected to decrease by 10 to 23% in 2040 in the North of the basin and increase by 55 to 118% in 2040 in the MENA countries (OME, 2018).

The observed and projected degradation of natural resources, freshwater availability, water and food quality can impact most socio-economic sectors (Ali et al., 2022), such as agriculture and tourism, as the Mediterranean Basin accounts for one-third of global tourism (Tovar-Sánchez et al., 2019). It will also impact maritime transport and trade, since the Mediterranean Basin accounts for 25% of all international seaborne trade (Manoli, 2021). Conflicts caused by resource scarcity and human migration are likely to increase due to drought, reduced suitable agricultural land caused by land salinisation due to sea level rise, desertification especially in the Southern and Eastern Mediterranean, and the deterioration of agricultural and fishery resources. However socio-economic and political factors are likely to still play a major role (Ali et al., 2022; Koubi et al., 2020).

1.3 WEFE nexus implementation in the Mediterranean

The Mediterranean faces challenges in water, energy, food, and ecosystem insecurity due to climate and non-climatic changes. These issues are characterised by large disparities between countries and multiple interlinkages between the WEFE components. The complex web of interactions can result in cascading effects, with changes in one pillar causing changes in the other, followed by multiple loops and feedback paths between the many interacting entities.

1.3.1 Data, indicators and assessments

In the Mediterranean Basin, the observation of available data has been key to the creation of monitoring tools and spatial indicators for nexus indexes and related SDGs specific to the region. They have been used to assess characteristics of WEFE pillar interdependencies and progress towards SDGs in the Mediterranean region. They have helped to highlight the high heterogeneity both within and between countries, making it possible to rank Mediterranean countries, and identify pathways to loosen inter-dependency between the water, food and ecosystem pillars to improve the impact of the nexus approach, especially when relying on renewable energy and enhanced efficiency in resource use (e.g. Casini et al., 2019; de Vito et al., 2017; Lacirignola et al., 2014; Papadopoulou et al., 2022; Saladini et al., 2018; Simpson et al., 2022). Regional assessments of nexus approach impacts are however limited by the lack of complete and disaggregated observations on the components of the WEFE nexus together with other issues related to their quality and accuracy. The unwillingness of authorities to provide certain types of required observations to researchers and other stakeholders also represents a major barrier to harmonised, integrated and interoperable data from different sectors and to wide adoption and application of the WEFE nexus in the Mediterranean region (Laspidou et al., 2020; Lawford, 2019; Markantonis et al., 2019; Saladini et al., 2018; Simpson & Jewitt, 2019).

1.3.2 WEFE nexus local implementation

At territorial level, both ecosystem-based solutions, which are cost-effective and community-oriented (Aguilera et al., 2013, 2020; Almenar et al., 2021), and technological solutions, which rely on technical innovation, have been implemented locally in the Mediterranean countries for more integrated and efficient resource use (de Roo et al., 2021; Hoff, 2011; Karabulut et al., 2019; Lucca et al., 2023; Malagó et al., 2021). A number of those solutions support food system sustainability while minimising water and energy demand (e.g. Casini et al., 2019; Daccache et al., 2014; El Gafy, 2017; El Gafy et al., 2016; Espinosa-Tasón et al., 2020; Huang et al., 2023; Lacirignola et al., 2014; Mayor et al., 2015). They include new irrigation techniques or recovering ancient ones, the use of renewable energy in agriculture, or bio-energy crop production in marginal areas[6], the use desalinated water, agrivoltaics, or agroecological practices, such as agroforestry and cover crops (e.g. Barron-Gafford et al., 2019; Harmanny & Malek, 2019; Hoff et al., 2019; Kalavrouziotis et al., 2015; Lequette et al., 2020; Martínez-Blanco et al., 2013; Pulighe et al., 2019). A large fraction of water is used throughout the energy industry for cooling thermal power plants, so more efficient cooling technologies are critical for the water-energy supply-demand balance (Qin et al., 2015; van Vliet et al., 2016). Smart water management, precision agriculture, water conservation and using integrated water management principles and practices may ensure water security in the Mediterranean (Papadopoulou et al., 2022). Implementing renewable energies in the Mediterranean region also benefits the water, ecosystem, food and energy pillars when it does not involve high environmental costs or resource degradation (e.g. Adamovic et al., 2019; Karabulut et al., 2019; Lange, 2019; Malagó et al., 2021; Pacetti et al., 2015). Behavioural solutions, such as adoption of the Mediterranean diet, including reducing meat consumption with differences among Mediterranean countries, and generally reduced consumption, have shown a high potential for adaptation and mitigation (Capone et al., 2014; El Bilali et al., 2017; García et al., 2023). Finally, digital solutions, like early warning

6 Marginal land is land that is of little agricultural or developmental value because crops produced from the area would be worth less than any rent paid for access to the area.

systems and climate services, have also shown broad applicability across various sectors in the Mediterranean (Cramer et al., 2018; de Roo et al., 2021; Dell'Aquila et al., 2023; Koutroulis et al., 2016; Marcos-Matamoros et al., 2020; Sánchez-García et al., 2022; Terrado et al., 2016). A model-based nexus approach assessment based on different climate, socio-economic and demographic change scenarios may finally help assessing the resilience level of sustainable development options and avoid maladaptation and unanticipated effects when changing variables in the system. This should be considered when designing integrated policies (e.g. Fader et al., 2016; Kebede et al., 2021; Khan et al., 2016; Martinez et al., 2018; van Vliet et al., 2016).

1.3.3 Upscaling local WEFE nexus experimentation to institutional implementation

In water-scarce regions like the Mediterranean Basin, water, food and energy are often not priced or allocated efficiently, so that resource use is not optimised (Wichelns, 2017). Several regional organisations in the region have launched programmes and initiatives to build mechanisms for supporting the WEFE nexus approach at various levels (Aboelnga et al., 2018). Upscaling the nexus approach from local experiments to global implementation however encounters difficulties. There is still a lack of concrete examples of global implementation of this approach, with many measures still designed in "silos" (Lange, 2019; Malagó et al., 2021; Zarei, 2020). This limited effective implementation of WEFE nexus approaches in the region is attributed to insufficient understanding of nexus trade-offs within science-policy-stakeholder interactions, insufficient incentives and limited vision, knowledge, development and investment (Hoff et al., 2019). The WEFE nexus approach also requires collaborative governance and involvement of stakeholders to develop meaningful policy objectives based on the principle of equity and social inclusion (Abaza, 2017; Ghodsvali et al., 2022; Halbe et al., 2015; Hoff et al., 2019; Jalonen et al., 2022; Karabulut et al., 2019; Sušnik et al., 2018). It also requires intra-Mediterranean trans-national collaboration to face the climate emergency and promote equitable sharing of the risks and burdens associated with sustainable development through the nexus approach (Bremberg et al., 2022; Lange, 2019; Malagó et al., 2021).

1.4 Report structure

In this report, the Water-Energy-Food-Ecosystem (WEFE) nexus is addressed as a key concept for a more resilient adaptation to the climate crisis in the Mediterranean region. It addresses the interlinked issues of water, energy and food security — and their connection with the surrounding ecosystems. Security issues, and therefore adaptation actions, are thus the key focus of this report, leaving the mitigation consequences of the nexus approach as potential synergies and trade-offs derived from the interconnections between WEFE components. The emphasis is on the nexus between water, energy and food security extending to the coasts of the Mediterranean Sea, and it does not focus on the details of the marine environment, including ecosystems, and the impact of other factors on its services. The following chapters detail and develop this introduction. The outline for this report was agreed upon by the Coordinating Lead Authors during the meeting in Barcelona (Spain) in June 2022 and underwent consultation with policymakers and stakeholders in December 2022. The report consists of a Summary for Policymakers (SPM), five main chapters and several annexes, as follows:

- Summary for Policymakers, including an Executive Summary.
- Chapter 1, **"Introduction: The Water-Energy-Food-Ecosystems (WEFE) nexus concept in the Mediterranean region"**, frames the motivation and main components of the MedECC WEFE nexus report.
- Chapter 2, **"Drivers of change and their impacts on the WEFE nexus in the Mediterranean region"**, focuses on the physical, biochemical and human drivers of changes to the WEFE components and how the changes cascade through the various components of the WEFE, sometimes with feedback on the drivers of change (*Figure 1.1*).
- Chapter 3, **"WEFE nexus adaptation and mitigation strategies"**, based on the analysis of the interactions between the various components of the WEFE nexus in Chapter 2, reviews the adaptation and mitigation measures adopted in the Mediterranean based on the nexus approach. It also identifies the challenges of mitigation and adaptation interventions (*Figure 1.1*).
- Chapter 4, **"Contributions of the WEFE nexus to sustainability"**, focuses on the link between the WEFE nexus approach and the United Nations (UN)

Sustainable Development Goals (SDG), especially SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 2 (zero hunger), SDG 14 (life below water) and SDG 15 (life on land) (*Figure 1.1*).

- Chapter 5, "Governance, policies and research options for the WEFE nexus", reviews the governance bodies to support the nexus approach in Mediterranean countries, policies implemented and research options for the WEFE nexus (*Figure 1.1*).
- Supplementary information is given in the annexes.

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Drivers of change and their impacts on the WEFE nexus in the Mediterranean region

2

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Chapter 2

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2

Executive Summary

The Mediterranean region faces a variety of drivers of change that operate at different spatial scales. These include climate change, land use changes, habitat alterations, air, soil and water pollution, population growth, industrialisation, urbanisation, lifestyle changes and conflicts (war). These drivers collectively impact the region's ecological and societal dynamics, including all the components of the WEFE nexus. Since the WEFE components follow complex hierarchical links and feedback, changes in one component can have cascading effects on other interconnected components, creating a complex web of interactions. To reduce the negative impacts of the drivers of change, the interlinkages among the WEFE components must be thoroughly evaluated at local scale, under a holistic view, to enable better-informed decisions and effective and more robust management policies. This chapter underscores the importance of recognising the interconnectedness of water, energy, food, and ecosystems in the Mediterranean region and the need for comprehensive assessment and management strategies to address the challenges posed by external environmental and social stressors.

Water security in the Mediterranean faces a multifaceted challenge stemming from a blend of factors, such as climate change, rapid population expansion in urban areas, unsustainable resource management and land use, and agricultural practices. The impacts of the drivers of change have negative effects on the availability and quality of water resources, but this effect will cascade, through a series of interactions, on the other components of the WEFE nexus, including crop yield reductions, alterations of agricultural commodity prices, reduction of electricity production and generation efficiency, desertification, habitat loss, and affecting vulnerable species.

Climate change, pollution, changes in diets, population growth, and urbanisation are inter-connected and contribute to the emergence of vulnerabilities through impacts on food availability, access and quality. There are substantial differences in terms of food security between Southern Europe and North Africa. Business as usual responses to address food security related challenges through industrialisation can lead to adverse effects on other WEFE components, such as increased soil and water pollution and GHG emissions, degradation of underground water resources, salinisation, loss of agrobiodiversity, and increase of energy demand and further greenhouse gas emissions.

The energy security of the Mediterranean region is significantly affected by a multitude of challenges from both the offer and demand sides. The escalating energy demands in the Mediterranean region are attributed to population growth, urbanisation and industrialisation. Moreover, addressing energy inequality is essential, as certain population segments have abundant energy access while others face deprivation. The dependence of the area on power generation methods that require significant amounts of water exposes them to the risk of decreased water availability and difficulties in managing water resources, due to the effects of climate change and the competition with other sectors. Similarly, competition for other resources to produce solar or wind energy, such as land for agricultural purposes and ecosystem services, further exacerbates the complex interplay within the nexus framework, showing the need to promote holistic analyses to address such challenge.

The pressures exerted on Mediterranean ecosystems impact their health resulting in ecosystem degradation, loss of biodiversity among others. These modifications disrupt the provision of multiple ecosystem services (namely, provisioning, regulating, and cultural) which subsequently have direct impacts on WEFE components as well as further cascading effects on other components of the WEFE.

2.1 The complexity of assessing the impacts of drivers of change on the WEFE nexus: the rationale of the approach

The ecosystems of the Mediterranean region provide many important resources and advantages, such as the ability to grow food for human consumption and industrial use, to enjoy the outdoors, and to foster artistic, cultural, and recreational pursuits. However, the physical parameters of the region, combined with the region's complex geographical (e.g. coastal vulnerability, water scarcity) and political issues (e.g. migration and refugee crises, territorial disputes), make it difficult to achieve environmental goals. Like other global ecosystems, the state of WEFE components and interdependencies between them serve as the defining characteristics of the Mediterranean ecosystem. Despite this, the spatial and temporal configuration of the WEFE nexus is undergoing substantial shifts linked to the drivers of change.

Drivers of change refer to all those factors that affect nature, anthropogenic assets, nature's contributions to people, and a good quality of life (Pörtner et al., 2021). A direct driver exerts immediate and noticeable impacts on the WEFE system, and can involve both natural change, such as earthquakes and volcanic eruptions, and anthropogenic factors like climate change, alterations in land and sea use, and air, water, and soil pollution (Sharif et al., 2020). On the other hand, indirect drivers of change are those that alter and influence direct drivers as well as other indirect drivers (also referred to as "underlying causes") and include, among others, demographic trends (population growth, urbanisation), technological innovations, lifestyle changes, and war (Odada et al., 2009). The impacts on the WEFE components are not isolated but are also the result of various interactions between two, three, or even all four WEFE components, such as water-food, energy-water, food-energy, ecosystems-water-food or water-food-energy interactions, among others. Within the WEFE system, cascading effects and interactions transpire across various temporal and spatial scales, ranging from local and short-term to regional, global, and long-term. Those interactions and cascading effects operate at a hierarchy of spatio-temporal scales. The complexity of this web of interactions is a big reason why the WEFE system in the Mediterranean changes in ways that are hard to predict. It should be noted here that, in the context of the WEFE system, the establishment of precise boundaries is of paramount importance to conducting a comprehensive assessment of the impacts of the drivers of change as well as of potential solutions. These 'boundary conditions' define the system's scope and spatial-temporal limits. The delineation of the system encompasses key parameters, including water resources, energy production, food systems, environmental ecosystems, and the geographic area or region under consideration. These boundary conditions may extend to include policy and governance structures that impact the WEFE system. In defining these boundaries, it is imperative to create a structured framework for understanding the interplay of drivers, components, and influences within the WEFE system, ensuring a comprehensive and contextually relevant evaluation. Also, understanding the complex interactions between the nexus components and how they can change and impact each other under different scenarios is crucial for identifying both positive synergies (e.g. sustainable land use and biodiversity) and negative trade-offs (e.g. hydropower dams and ecosystems) between these components. This approach makes it possible to design cross-sectoral adaptations, as shown by Kebede et al. (2021). Furthermore, it enhances our understanding of how these interactions impact the long-term health and productivity of ecosystems.

2.1.1 Drivers of change related to WEFE in the Mediterranean

2.1.1.1 Climate change

The Mediterranean is situated in a transitional zone between the mid-latitude and sub-tropics. The Mediterranean region has been labelled a "hotspot" for climate change due to its predicted warming and drying (Diffenbaugh et al., 2007; Giorgi & Lionello, 2008; Lionello & Scarascia, 2018). There is strong evidence that the twentieth century was marked by a general warming and by a more pronounced summer warming (El Kenawy et al., 2012; El Kenawy et al., 2019; Pfahl, 2014; Ulbrich et al., 2012). The observed rates of climate change are higher than global trends for most variables (*Figure 2.1*). Similarly, since 1950, heatwaves have become more frequent (Baldi et al., 2006; Ibrahim et al., 2021; Kuglitsch et al., 2010). Also, both the frequency and severity of droughts have increased (Cook et al., 2016;

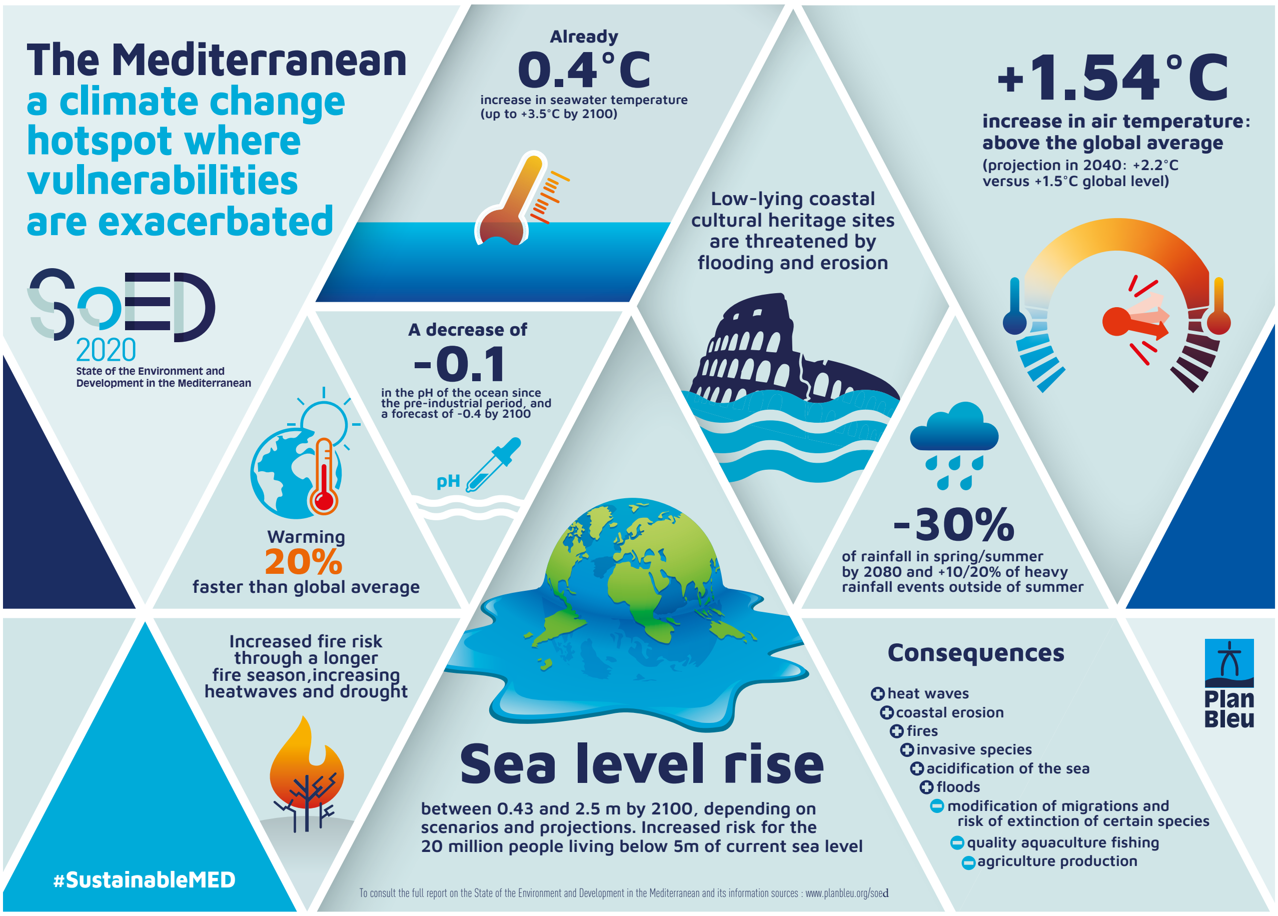

Figure 2.1 | Climate and environmental change in the Mediterranean.
Source: UNEP/MAP & Plan Bleu (2020).

Hoerling et al., 2012; Sousa et al., 2011; Tramblay et al., 2020a; Vicente-Serrano, 2007). These observed changes have been in line with global trends and can be attributed in part to decadal variability associated with circulation patterns like the North Atlantic Oscillation (NAO) (Meyssignac et al., 2011; Ozgenc Aksoy, 2017; Raymond et al., 2018; Tsimplis et al., 2013).

The Mediterranean region's climate will likely become warmer and drier in the twenty-first century (*high agreement; robust evidence*, especially for air temperature) (Drobinski et al., 2020b; Lionello & Giorgi, 2007; Nashwan et al., 2020; Planton et al., 2012; Taïbi et al., 2019; Zittis et al., 2019). The results show that future warming is expected to occur across the year, with the effects being more pronounced during summertime and on land, as opposed to the ocean (El Kenawy et al., 2013; Giorgi & Lionello, 2008). More frequent high-temperature events and heatwaves are thought to be linked to these increased temperatures (Jacob et al., 2014). Summer rainfall is expected to decrease by 10–15% in southern France, northwestern Spain, and the Balkans as a result of a global atmospheric temperature increase of 2°C and by as much as 30% in Türkiye and Portugal (Vautard et al., 2014). In recent decades, summer temperatures in the Mediterranean region have risen at a faster rate than those observed in the Northern Hemisphere and even more rapidly than the global mean, along with an increase in the frequency of intense heat waves. It is projected that future warming in the Mediterranean region will be 25% faster than the global mean, with summertime temperatures increasing 40% faster than the global mean (Lionello & Scarascia, 2018). The aforementioned consensus is established by taking into account multiple lines of evidence—observations, regional and global model projections, and an extensive comprehension of the underlying mechanisms—all of which contribute to a high level of confidence regarding observed and projected warming patterns in the Mediterranean region

(Doblas-Reyes et al., 2021). With respect to the pre-industrial period, average global warming of 1.5°C is predicted to reduce mean rainfall by 4% in much of the region, especially in the south, and increase the length of dry spells by 7% (Lionello & Scarascia, 2018). Reduction of precipitation will affect all seasons in central and southern Mediterranean areas, with maximum reduction for winter precipitation (−7% for the southern Mediterranean region). The length of meteorological dry spells (Schleussner et al., 2016) and meteorological, hydrological, and agricultural droughts is expected to increase significantly (IPCC, 2021; Kelley et al., 2015; Tsanis et al., 2011). In the same context, by 2100, the coast of southern Italy is predicted to be severely flooded (Scardino et al., 2022). Streamflow patterns are projected to shift, with spring's high flows diminishing earlier, summer's low flows becoming more intense, and winter's greater and more erratic discharge occurring earlier. Flooding is more likely to happen in most of the Mediterranean Basin because extreme rainfall is expected to get worse and happen more often (e.g. Drobinski et al., 2018; Tramblay & Somot, 2018). As stormwater management systems are generally not well planned in the Mediterranean, people who live in flood-prone areas are more exposed and vulnerable (Llasat et al., 2013).

Rising temperatures, coupled with drought and land-use change, are predicted to increase fire risk, lengthen fire seasons, and increase the frequency of large, severe fires (Gouveia et al., 2017; Santonja et al., 2017). It is also anticipated that future climate change will exert significant and diverse effects on marine ecosystems. Sea surface temperatures in the Mediterranean demonstrate a complex panorama of both regional and temporal variability with a prevailing warming tendency in sea surface temperature (SST), which is likely to continue under future warming scenarios (Axaopoulos & Sofianos, 2010; Pastor et al., 2018; Shaltout & Omstedt, 2014). In accordance with SST rise, a consistent decrease in pH in the Mediterranean Sea has been observed, signalling ocean acidification (Flecha et al., 2015; Kapsenberg et al., 2017). This phenomenon is attributed to the absorption of CO_2 from the atmosphere (Kapsenberg et al., 2017; Solidoro et al., 2022), with acidification particularly pronounced in the Western basin (Hassoun et al., 2015). Nevertheless, despite this acidification, the Mediterranean Sea remains highly supersaturated in calcium carbonate minerals (Hassoun et al., 2015). Projections indicate that acidification will persist, with the Eastern Mediterranean facing particularly acute effects (Reale et al., 2022a, 2022b). In the high IPCC emission scenario SRES-A2, nitrates are expected to build up in the seawater around the Mediterranean, but phosphorus does not seem to be changing. This means that low-phosphorus areas will increase (Richon et al., 2019).

Due to recent and future climate change, changes in the provision of ecosystem services may exacerbate social conflict and cause people to be forced to relocate (van der Geest et al., 2019). A representative example is found in the Egyptian Delta, where salinisation and erosion of agricultural lands forced farmers to relocate (Ahmed et al., 2014). Climate change and drought, in particular, have emerged as substantial contributors to the Syrian conflict, as they induced forced migration from the eastern to mainland regions of the country (Butler, 2018; Gilmore et al., 2018; Ide, 2018; Selby et al., 2017). When resources are scarce, attempts to mitigate one risk may weaken human communities or make other risks worse. The Mediterranean Basin has a long history of political and social unrest because of its complex cultural, geopolitical, and economic landscape. Extra climate-related stresses in the Mediterranean Basin increase human insecurity by making local communities there more susceptible to harm. As such, there has been an increase in vulnerability due to mismanagement and overexploitation of natural resources over the past century (Bremberg et al., 2022; Ide, 2018; Mycoo et al., 2022).

2.1.1.2 Land Use and Land Cover Changes (LULCC)

The high importance of Land Use and Land Cover Changes (LULCC) is recognised by the UN for fields ranging from biodiversity conservation to food security, disaster risk reduction, climate change, and sustainable development. The Mediterranean region has inherited a mosaic-structured landscape determined by heterogeneous topography, soils, water resources and vegetation (Lana-Renault et al., 2020). In this sense, there is a clear contrast in LULCC trends between the northern Mediterranean countries (225 million inhabitants) and the southern and eastern countries (335 million inhabitants). The land cover (LC) of an area is what is observed at the surface, with either vegetation and naked areas (e.g. from natural to agricultural ecosystems) or anthropogenic constructions (e.g. urban surfaces). Land Use (LU) is the management of those areas, to maintain or change their cover. One of the main drivers of LULCC is population dynamics, which show highly contrasting patterns in the Mediterranean: northern regions have seen population growth stabilised (FAO & Plan Bleu, 2018; PRB, 2019), causing diverging patterns of land use (i.e. land abandonment in low-productive mountainous areas and concentration of economic activity in valleys and coasts), and population growth in the southern and eastern regions has resulted in increasing demand for land for agricultural production and livestock pastures (FAO & Plan Bleu, 2018; Winkler et al., 2021).

A declining rural population in northern Mediterranean countries has led to the abandonment of crops and farmland, and to the reduction of livestock grazing, with the subsequent regeneration of forests and scrublands (Debussche et al., 1999; García-Ruiz & Lana-Renault, 2011; Moreno-de-las-Heras et al., 2019; Vicente-Serrano et al., 2019). Additionally, extensive afforestation programmes have been implemented in recent decades by northern countries' governments to enhance the environmental value of abandoned farmlands in the highlands and control hydrological and soil erosion processes (Ortigosa et al., 1990; Vallauri et al., 2002). Altogether, this has resulted in relevant environmental consequences, including changes in the water cycle (see *Section 2.3.1.1*), soil erosion and hydrological connectivity alterations, and biodiversity changes (see *Section 2.5.1.2*), among others. Moreover, revegetation processes have relevant implications regarding wildfire risks due to increased fuel load and biomass volume (Lana-Renault et al., 2020; Pausas & Fernández-Muñoz, 2012; Pausas & Millán, 2019). Intensive agriculture experienced significant growth in the more populated lowlands and coastal areas, with the goal of meeting the demand of national and international markets (Bellot et al., 2007; Serra et al., 2008). These changes have led to a significant expansion of irrigated areas in order to increase agricultural productivity and favouring the cultivation of new crops with higher requirements than the traditional Mediterranean triad (grapes, grains, and olives) (Tanrivermis, 2003). The most remarkable example of this process has been seen in Spain, where the extent of irrigated areas has doubled over the last six decades, from 1.8 million hectares in 1961 to 3.7 million hectares in 2019 (FAO, 2023). In the Southern Mediterranean, countries with higher demographic pressure have followed strategies based on land clearing, livestock breeding and wood gathering for heating (Barrow & Hicham, 2000; Johnson, 1996). These processes resulted in smaller forest areas than the ecological potential of southern and eastern countries (FAO, 1994; Lana-Renault et al., 2020), where high human pressure on forest ecosystems prevails in rural and mountainous areas, resulting in woodland degradation (Chebli et al., 2018; del Barrio et al., 2016; Nsibi et al., 2006). Still, intense urbanisation and associated expansion of agricultural areas are the main causes of deforestation in southern and eastern regions (Belaid, 2003; del Barrio et al., 2016).

Tourism development is another key factor in explaining LULCC trends. The Mediterranean region ranks amongst the world's top tourist destinations, accounting for 30% of global tourist arrivals (UNWTO, 2017). International tourists grew from 58 million in 1970 to 349 million in 2015, and these figures are expected to grow to reach 500 million by 2030 (UNWTO, 2017). The spatial pattern of tourism occupation is mainly concentrated in coastal areas, where strong urbanisation has occurred across the Mediterranean Basin (Shalaby & Tateishi, 2007; Sonmez & Sari, 2007), leading to significant forest regression and habitat fragmentation caused by urban sprawl (Hepcan et al., 2012; Jomaa et al., 2008) and a significant increase in water demand (see *Section 2.3.1.2*).

Past assessments and future predictions of LULCC involve a high degree of uncertainty (Anav et al., 2015). The future of forest cover in the Mediterranean is uncertain, with climate change and human activities posing significant challenges. Touhami et al. (2023) highlights the impact of the projected warming climate on forest ecosystems in Tunisia. Donmez et al. (2011) provides specific climate and productivity projections, providing estimations of net primary productivity in Turkish pine forests. However, numerous studies stress the need for mitigation and adaptation strategies to sustain forest ecosystem services in the face of changing land use and climate (e.g. Appiagyei et al., 2023).

2.1.1.3 Pollution

Industrial pollution is a major environmental concern in the region, as pressures from land-based sources remain high (EEA, 2014). Attention is given to key sectors: the production of energy, manufacture of refined petroleum products, treatment of urban wastewater, food packing, and manufacture of cement and metals. In particular, the manufacture of refined petroleum products is responsible for about 60 to 70% of nutrients and oxygen-depleting substances present in pollution. Southern and eastern countries are responsible for the largest share of biochemical oxygen demand measured in a water sample during 5 days of incubation at 20°C (BOD5) emitted by this sector for the whole Mediterranean. This means that while energy commodities are traded around the region, the adverse effects in terms of local pollution are concentrated in few areas. Chromium and cadmium emissions are also associated with energy refining processes (EEA & UNEP/MAP, 2014). Instances of industrial emissions, particularly in the Southern Mediterranean, have registered levels exceeding 100 µg m^{-3} of fine particulate matter (PM2.5), in stark contrast to the global average of 39.6 µg m^{-3} and the European Union's average of 14.2 µg m^{-3} (UNEP/MAP & Plan Bleu, 2020). Alarmingly, two-thirds of Mediterranean countries surpass the World Health Organization's recommended threshold for air pollution concerning both particulate matter and ozone (UNEP/MAP & Plan Bleu, 2020).

Disturbingly, nearly half (49%) of Mediterranean water bodies fail to achieve a good environmental status (EEA et al., 2020). The region generates a staggering 184 million tonnes of solid waste annually, characterised by low recycling rates. Additionally, the presence of emerging contaminants, such as pharmaceuticals, cosmetics, flame retardants, and plastic additives, poses a significant threat. These contaminants have poorly understood life cycles and impacts, and are potentially toxic and resistant to conventional wastewater treatment methods (EEA et al., 2020). Pollution in the Mediterranean is predominantly attributed to heavy metals, exacerbated by the continuous discharge of both treated and untreated wastewater. This pollution stems from various sources, including the production and processing of metals, energy production, pulp and paper manufacturing, chemical industry activities, and intensive farming and aquaculture practices (Ochoa-Hueso et al., 2017; Sicard et al., 2023). Heavy metals and mineral oils are responsible for approximately 60% of soil contamination in the region (Ballabio et al., 2018; Ferreira et al., 2022; Panagos et al., 2013). Nevertheless, the levels of heavy metals (cadmium, mercury, and lead) in coastal waters, assessed against Background Assessment Concentrations (BAC) and Environmental Assessment Criteria (EAC) through bivalves and fish, generally demonstrate an environmentally acceptable status (UNEP/MAP & Plan Bleu, 2020). On the other hand, the Mediterranean region stands as one of the most severely impacted areas globally in terms of plastics, with an alarming 50% of marine litter found on the seabed being composed of plastic. Microplastic concentrations on the surface of the Mediterranean Sea surpass acceptable limits, exceeding 64 million floating particles per square kilometre. Additionally, underwater noise pollution is a growing environmental concern with significant implications for marine life in the Mediterranean.

2.1.1.4 Population growth, industrialisation, urbanisation, migration, lifestyle changes, war

About 6% of the global population make home in the Mediterranean region (UNEP/MAP, 2016). According to World Bank data (*Figure 2.2*), total population growth in the Mediterranean region has remained at about 1% yr^{-1}, but with clear differences between regions and countries, a change over the decades, and a clear impact of the major conflicts that have affected the region (World Bank, 2021). In absolute terms, the Mediterranean population grew by 259 million inhabitants in fifty years (+84%), from 1970 to 2020, to reach 542 million people. Eighty-five percent of this increase (216 million inhabitants) occurred in the South and East Mediterranean, as a result of improved economic conditions and improved health services (World Bank, 2021). With current demographic trends, the Mediterranean population is expected to further grow by more than 100 million inhabitants until 2050 (UN DESA, 2022). Again, most of this increase will be concentrated in the South and East Mediterranean, in particular in the two densely populated countries of Egypt and Türkiye, which together represent more than one-third of the Mediterranean population. By

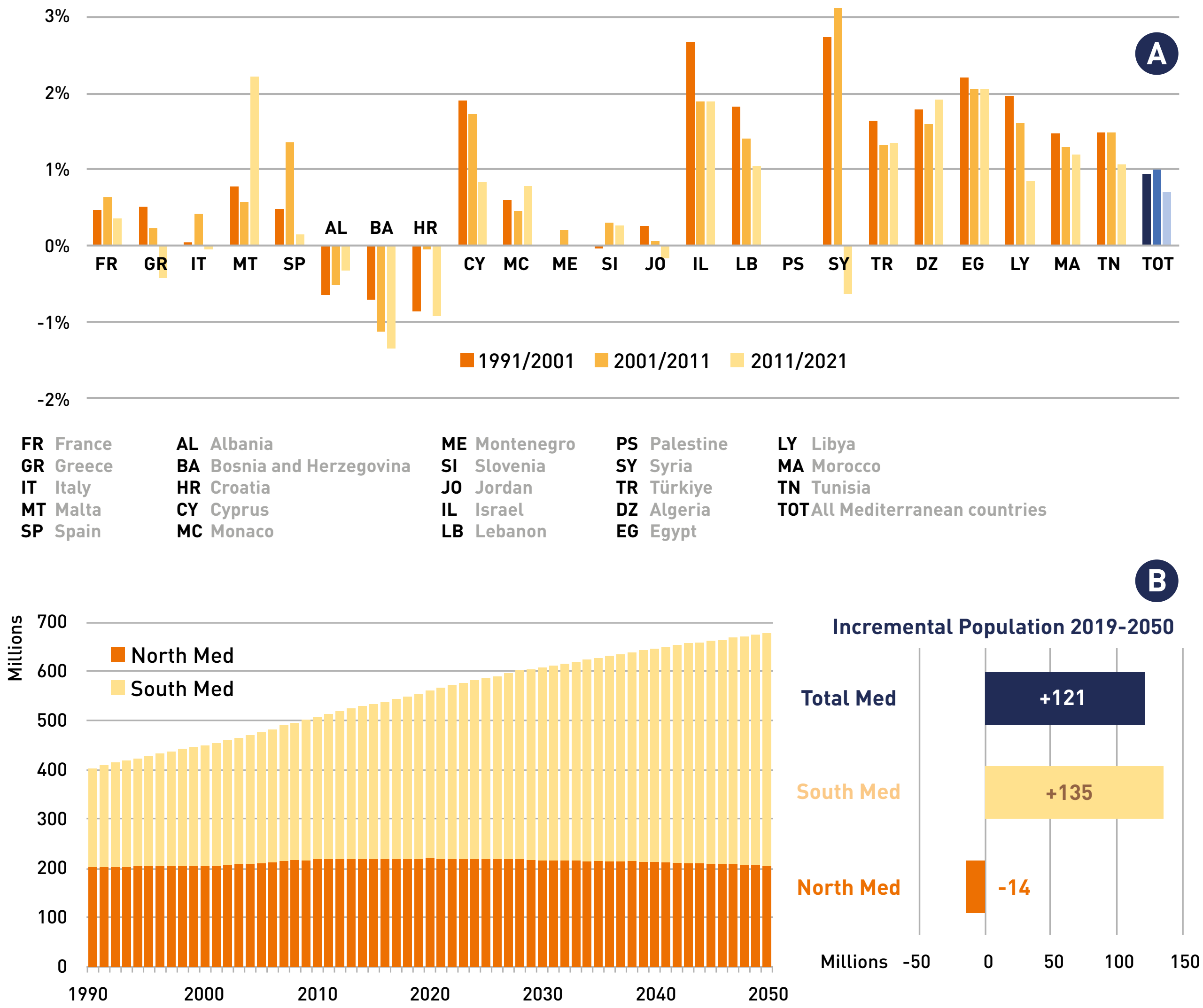

Figure 2.2 | (A) Population growth rates in the countries of the Mediterranean region in recent decades (based on World Bank, 2021) and **(B) current and projected demographic trends in the Mediterranean up to 2050** (OME based on UN DESA (2022).

2050, the southern Mediterranean's share in total Mediterranean population is projected to increase to 70%, while the northern Mediterranean will see its population ageing and its share decrease to 30%. In 2050 nearly half of the Mediterranean population is projected to be concentrated in three countries (Algeria, Egypt, Türkiye) (*Figure 2.2*). Since 1960, the rural population has increased at a lower rate in southern and eastern countries, with stabilisation expected by 2030, and considerably decreased in the northern countries (Lana-Renault et al., 2020; PRB, 2019). Population growth in southern and eastern Mediterranean countries is expected to develop through urban growth, mainly in coastal areas, reaching 75% of urban population share by 2050 (48% in 1960 and 68% in 2015).

Industrialisation and urbanisation are often analysed as sub-processes of modernisation, which is also accompanied by lifestyle changes resulting primarily from technological development. The Mediterranean region has witnessed rapid urbanisation over the past few decades, especially in the northern African and eastern Mediterranean regions, where data shows that the percentage of urban population in 2020 was almost 60% (still lower than the 75% for the Northern Mediterranean), up from slightly above 30% in 1960 (World Bank, 2021). By 2050, the urban population is projected to exceed 70% in both regions, and 80% in Southern Europe (World Bank, 2021). Taking into account increasing population and urbanisation trends, especially in coastal areas, southern and eastern Mediterranean countries will face a particular challenge in enabling sustainable urban development policies. Lifestyle changes have been accompanied by higher consumption of energy and materials. This increase, especially among affluent populations in the Global North, is accompanied by an increase in greenhouse gas emissions elsewhere, and evidence shows that luxury consumption can be more difficult to decarbonise than that of people living at sufficiency level (Millward-Hopkins, 2022). Rapid urbanisation in the Mediterranean region has led to several challenges, including inadequate housing, poor infrastructure, traffic congestion, and air pollution (Battarra & Mazzeo, 2022; Tourret, 2006). In addition, some urban residents in North Africa are living in informal settlements, and in the Eastern Mediterranean some urban areas have limited access to basic services such as water and sanitation (Mancuso et al., 2020). There is a growing awareness of the need for sustainable urban development and the adoption of smart technologies to improve urban infrastructure, transportation, and energy systems (Battarra & Mazzeo, 2022).

Migration plays a significant role in urbanisation in the Mediterranean region. Many people migrate from rural areas to cities in search of better job opportunities, education, and healthcare (Miftah, 2018). In addition to internal migration, many North Africans and sub-Saharans migrate to Europe, including cities in Southern Europe, in search of better economic opportunities (Schwan & Yu, 2018). Urban areas in eastern Mediterranean countries have been a major destination and transit point for refugees and migrants from conflict-torn countries like Afghanistan, Iraq, and Syria (Taghizadeh Moghaddam et al., 2017). Migration is also linked to geopolitical instability, which favours an increasing flux of immigrants from sub-Saharan Africa to Mediterranean countries, further stimulating the demand for energy, food, and water, and thus, further increasing the nexus challenges.

The period following the end of the Cold War has been marked by several wars and conflicts in the Mediterranean region, or in its direct vicinity, which have had very significant repercussions in terms of human lives, and serious effects on health, the economy, and the environment, all of them with close connections to the WEFE nexus. The Arab Spring had a major impact in the region, with effects ranging from constitutional reforms in Morocco and the overthrow of the regime in Tunisia and Egypt, to much more devastating effects in Libya and Syria (Muhammadsidiqov, 2015). The civil wars in Libya, in 2011, and then between 2014 and 2021, have cost thousands of lives and displaced hundreds of thousands of civilians (Müller-Funk, 2023). In Syria, the death toll from the ongoing conflict is in the hundreds of thousands, many of whom are civilians (Üngör, 2023). The war in Syria has also caused the destruction of the country's infrastructure and the displacement of millions of refugees to neighbouring countries, Europe and elsewhere. Finally, the Russo-Ukrainian conflict which started in 2022 represents another major challenge to regional and global peace, and a significant economic impact. Implications for the Mediterranean region include heightened uncertainty and the redirection of public spending towards security and rearmament (Fiott, 2022). WEFE is also impacted, for instance through ecosystems degradation, gas supply problems (see *Section 2.4.1.5*), especially for European countries, and food security challenges (see *Section 2.3.1.3*) for countries that depend on food imports from Ukraine and Russia (Liadze et al., 2023), particularly in the MENA region (Quagliarotti, 2023).

2.1.2 The cascading effects of nexus interactions on WEFE components

The WEFE nexus components and their spatio-temporal interdependencies behave as complex systems. These systems typically include multiple loops and feedback paths between many interacting entities – in this case, the nexus components – together with inhibitory connections and preferential reactions. The complex web of interactions between WEFE components can therefore result in feedback loops through which changes in one WEFE component, mediated by the impacts of drivers of change and associated responses, may result in changes in other WEFE components, as well as in the drivers of change themselves (*Figure 2.3*). For instance, changes in water availability due to climate change (or other drivers of change) can impact food production and energy generation. Reduced food availability may require increasing

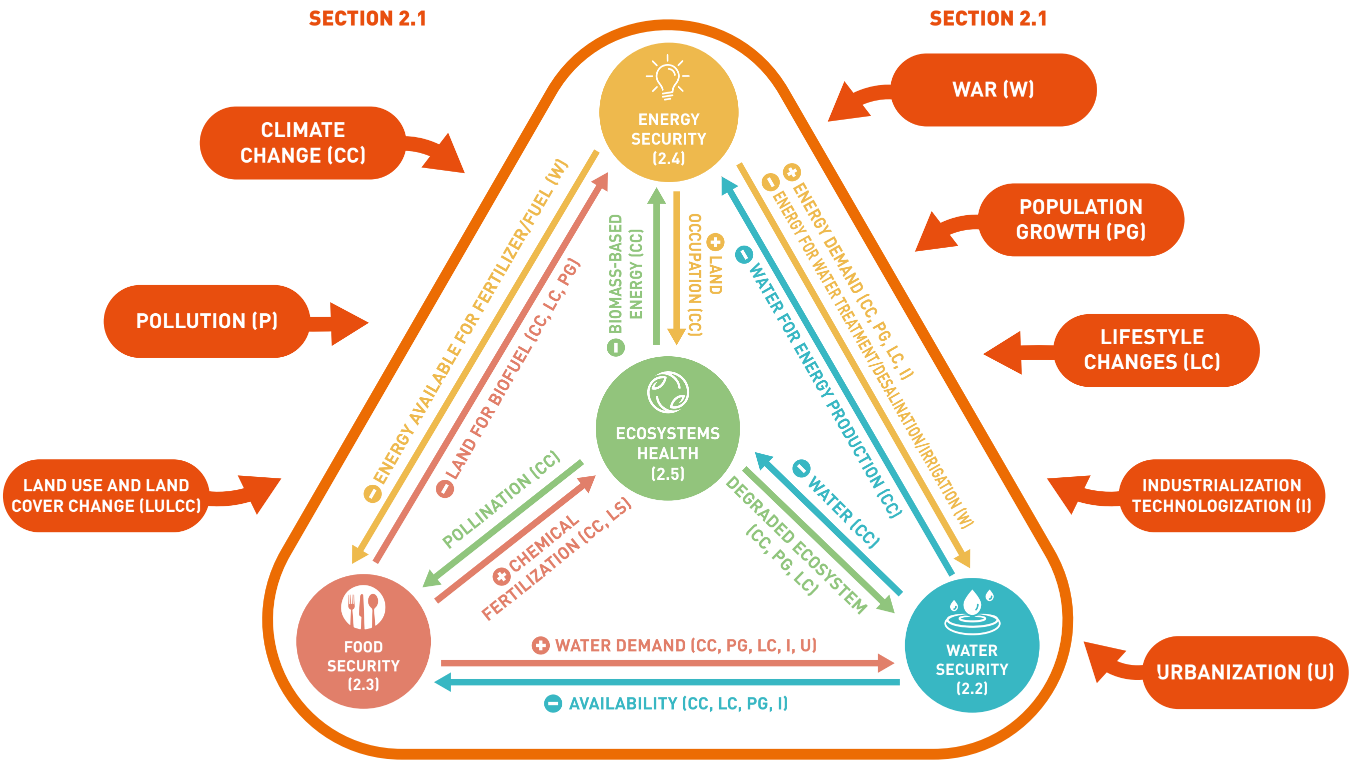

Figure 2.3 | Schematic figure of the rationale of Chapter 2.
Orange outer boxes represent the indirect (right) and direct (left) drivers of change (*Section 2.1*). Inside the box are the nexus components (WEFE) and examples of interactions between them, mediated through the drivers of change (in brackets). These interactions lead to feedback loops and cascading impacts through which nexus components become drivers of change for other nexus components (*Sections 2.2 and 2.5*).

yields, which then requires more water, further reducing the amount of water available for food, energy, ecosystems, and other uses. Furthermore, depending on the techniques used to increase yields, it may result in more greenhouse gas emissions and therefore reinforce climate change. It is important to bear in mind that drivers of change also generate those cascading effects between them. For instance, industrialisation or lifestyle changes contribute to climate change, while climate change may generate conditions that facilitate conflicts for resources, rural to urban migration and thus, increased urbanisation.

In line with this cascade rationale, in this chapter we describe, for each nexus component (water, food, energy, ecosystems), how the drivers of change described in *Section 2.1.1*, impact each WEFE component in particular (*Sections 2.2.1, 2.3.1, 2.4.1 and 2.5.1*). In a second step, we then analyse how those impacts can trigger different interactions and feedback loops between the WEFE components as well as the drivers of change themselves (*Sections 2.2.2, 2.3.2, 2.3.3, 2.4.2, 2.5.2, 2.5.3*). We call these interactions cascading impacts, that can occur downstream and upstream. Given the endless number of potential interactions between the drivers of change and WEFE components, for illustrative purposes and space constraints, we have assessed the mechanisms at play related to one or two drivers of change, for each component, with climate change common to all of them. *Figure 2.3* presents some examples of interactions between WEFE components which reflect the rationale of this chapter.

2.2 The WEFE cascade from the water change perspective

2.2.1 Impacts of drivers of change on water security

Water security in the Mediterranean is threatened by a combination of factors, including climate change, densely concentrated population growth, and unsustainable resource management and land use practices, among others (Daccache et al., 2014; Fader et al., 2020; Scheffran & Brauch, 2014). Climate change has caused an increase in temperature and more frequent and severe drought conditions in many areas of the Mediterranean region (García-Ruiz et al., 2011; IPCC, 2022; Samaniego et al., 2018). Population growth, economic development and lifestyle changes have led to increased water demand, resulting in water shortages and depletion of water resources (Labrousse et al., 2022; Rico-Amoros et al., 2009; Scheffran & Brauch, 2014; Schilling et al., 2012). Moreover, unsustainable resource management and inefficient irrigation practices (Bousbih et al., 2018; Martínez-Granados et al., 2011) have resulted in pollution of water resources (Lutz et al., 2016), groundwater depletion (Dalin et al., 2017; García-Ruiz et al., 2011; Wada et al., 2010). A combination of these factors has created many uncertainties regarding water security in the Mediterranean region that are set to increase during the coming decades in the context of climate change (IPCC, 2022; Malek et al., 2018).

2.2.1.1 Climate change

Some inherent characteristics of the Mediterranean climate (e.g. irregular spatio-temporal distribution of precipitation, very high evaporative demand in summer and high frequency of climate-related extreme events (droughts and floods) (Caloiero et al., 2018a; Deitch et al., 2017; García-Ruiz et al., 2011; Mateos et al., 2023) are being exacerbated by climate change, considerably reducing water security in the Mediterranean region on an increasing basis, with climate change impacts projected to continue occurring in the region with even more frequency and intensity (IPCC, 2022; Noto et al., 2022). Under a 2°C warming scenario, water resources in the Mediterranean region are expected to decrease by 2 to 15% (Cramer et al., 2018) with a likely increase in dry spell lengths (Noto et al., 2023; Raymond et al., 2019; Schleussner et al., 2016). For instance, the Water Scarcity Index is expected to be medium or high for a large portion of the Mediterranean region by 2050 (Caretta et al., 2022). Under future climate change scenarios, per capita water availability in Greece and Türkiye may drop below the generally accepted threshold for severe water stress of 1000 m^3 yr^{-1} in 2030 (Ludwig et al., 2010). Decreasing water resources in the Mediterranean region has been attributed to changes in precipitation (García-Ruiz et al., 2011), especially in the southern region (Caloiero et al., 2018a), subsequently transmitted to other components of the hydrological cycle (i.e. runoff and river discharges, groundwater levels) (Dai et al., 2009; Finger et al., 2012; Kurylyk et al., 2014; Touhami et al., 2015), and to an observed and projected increase in atmospheric evaporative demand through rising temperature (IPCC, 2022; Noguera et al., 2021; Vicente-Serrano et al., 2018), leading to increasing evaporative losses (Cherif et al., 2020).

Decreasing precipitation trends are predominant in the Mediterranean region (García-Ruiz et al., 2011), with reductions in annual precipitation ranging from 10 to 20 mm per decade due to spatial variability (Achite et al., 2021; Noto et al., 2022; Vicente-Serrano et al., 2019). Decreasing summer trends are even worse, especially in the southern countries (Caloiero et al., 2018a), whereas dry spells have also become more intense, frequent, and protracted (Caloiero et al., 2018b). Future precipitation projections for the Mediterranean region forecast reductions ranging from 5 to 40%, depending on the emission scenario, with critical consequences for other components of the hydrological cycle and freshwater sources (IPCC, 2022). Under a 2°C warming scenario, the frequency and duration of meteorological droughts are projected to double in southern countries, and agricultural droughts are projected to be 150 to 200% more likely (IPCC, 2022). Furthermore, precipitation extremes have increased in specific northern regions, and future projections indicate a further rise in the north (for global warming levels surpassing 2°C), while there is no notable change indicated for the south (IPCC, 2022). This may potentially be linked to an increased occurrence of flash floods, exacerbating water insecurity through their impacts on water infrastructure.

General decreasing trends in precipitation have reduced runoff and river discharges in many river basins around the region. Moreover, revegetation processes and increasing evapotranspiration are exacerbating streamflow drought, rather than meteorological drought, characteristics (Peña-Angulo et al., 2021) (see *Section 2.2.1.2*). Future projections of declining precipitation, together with increased evaporation in the Mediterranean region, will likely cause a decrease in runoff, which, depending on the warming scenario, is expected to range between 5% (at 1.5°C warming) and 25% (at 2°C warming) (Droogers et al., 2012; Mariotti et al., 2015), resulting in a decrease of surface water resources especially in southern countries (Fader et al., 2020; Tramblay et al., 2018).

Groundwater is of vital importance for water security in many Mediterranean areas (Fader et al., 2020). Projections of climate change impacts on groundwater estimate reductions of around 12% for aquifer recharge in continental Spain over the coming decades (Pulido-Velazquez et al., 2018), reaching 58% in some areas (Pulido-Velazquez et al., 2015). Reductions range from 20 to 50% in western Türkiye (Ertürk et al., 2014), are projected to reach almost 30% in Tunisia by 2050 (Fader et al., 2020), and up to 25% in Morocco and Portugal by the end of the century (Stigter et al., 2014). Moreover, in coastal aquifers, salinisation created by seawater intrusion has become a first order issue for freshwater and agricultural supply (Guyennon et al., 2017; Pisinaras et al., 2021; Pulido-Velazquez et al., 2018).

The 1.5°C warming suffered in the Mediterranean, exceeding 2°C in summer (IPCC, 2022), has led to increased atmospheric evaporative demand with adverse consequences for water availability. Outcomes can be summarised as follows: (1) increased evapotranspiration by vegetation, with revegetation having a prominent role in explaining these trends in mountainous and rural areas (Labrousse et al., 2022; Lana-Renault et al., 2020; Llorens & Domingo, 2007); (2) increased evaporative loss from lakes and reservoirs (Martínez-Granados et al., 2011; Zhao et al., 2022); (3) increased severity of hydrological droughts caused by increased evaporative demand (Noguera et al., 2021; Vicente-Serrano et al., 2014); and (4) declining aquifer recharge due to increased evaporative rates and increasing water demand for crops (Bellot et al., 2007; Leduc et al., 2007).

Climate change affects not only water availability but also water quality through changing precipitation, temperature variability, frequency, and occurrence of extreme events (Nijhawan & Howard, 2022). Climate change may have an impact on nutrient and mineral exports. It could lead to a decline in nitrogen export due to a decrease in runoff and erosion (Lutz et al., 2016; Molina-Navarro et al., 2014; Serpa et al., 2017). In contrast, phosphorus exports could increase under some scenarios (Molina-Navarro et al., 2014), and copper should be little affected due to its strong immobilisation in soils (Serpa et al., 2017). Nevertheless, changes in water quality could vary markedly depending on the scenarios considered and land uses. Reservoir water quality may also be affected due to close coupling between the projected trend of decreasing streamflow and the risk of anoxia (Marcé & Armengol, 2010) and the direct implications on nutrient cycles, constraining future domestic water supply by water quality problems associated with phosphorus loads (Rocha et al., 2020). These effects could be boosted by a rise in water temperature (Sánchez-Arcilla et al., 2011), decreasing the amount of dissolved oxygen in the water and reducing the mass transfer between deep and surface waters. Other challenges to water quality in coastal areas will probably arise from salt-water intrusion driven by sea level rise and enhanced extraction by higher irrigation demand (Cramer et al., 2018).

With regard to extreme events, more frequent and intensive droughts can also affect water quality, because lower water flows reduce the dilution of pollutants (e.g. organic matter, heavy metals). Groundwater quality will also be affected by reduced water flows, conditioning stream-aquifer interactions, subsurface recharge and aquifer overuse, leading to a general modification of nitrate in the groundwater as dilution varies (Mas-Pla & Menció, 2019). Conversely, while augmented precipitation enhances dilution and contributes to enhanced water quality, the occurrence of floods poses a counterbalancing risk. Flood events have the potential to elevate the discharge of pollutants, resulting in the contamination of surface and groundwater bodies with untreated wastewater and leachate from solid waste (*Figure 2.4*).

2.2.1.2 Land Use and Land Cover Changes (LULCC)

LULCCs alter water balance and partitioning of precipitation between evapotranspiration, runoff, and groundwater flow (Foley et al., 2005). One of the most significant LULCCs observed in Mediterranean regions (especially in northern countries) is the revegetation process that has occurred in recent decades, following farmland abandonment in many mountainous and rural areas (see *Section 2.2.1*). From this perspective,

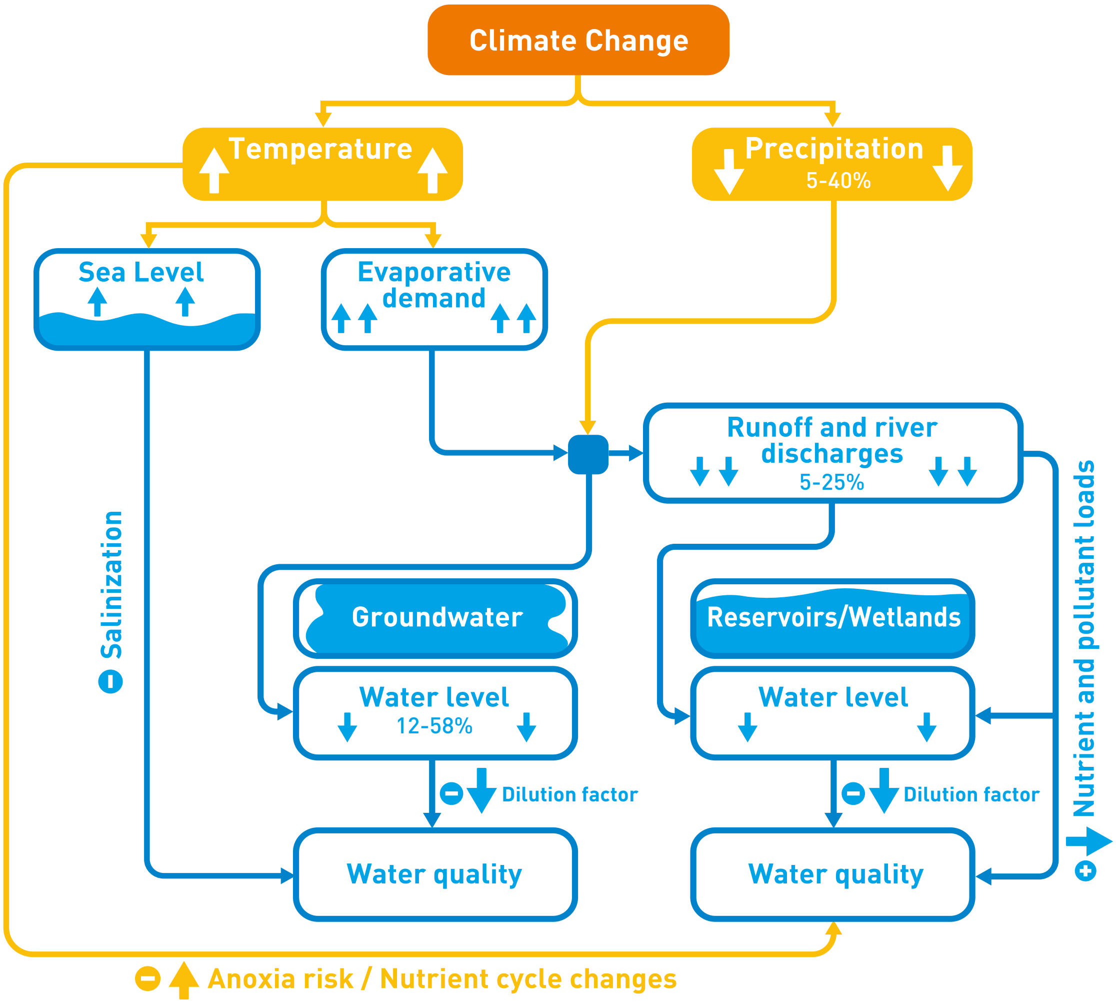

Figure 2.4 | Main impacts of changing mean climate trends on water availability and quality in the Mediterranean region. Up and down arrows indicate an increase and a decrease, respectively. The symbols + and – represent a positive and negative impact, respectively. The blue box represents a virtual water pool.

forest cover presents enhanced evapotranspiration and interception rates, increasing water consumption by vegetation, and water yield therefore usually increases when forests are transformed into systems with lower biomass, and decreases after revegetation processes (Andréassian, 2004; Bosch & Hewlett, 1982; El Hafyani et al., 2020; Lana-Renault et al., 2020).

Shrub and forest expansion processes, encouraged by farmland abandonment, are associated with decreasing river discharges in many areas within the Mediterranean region, including the Pyrenees (Beguería et al., 2003; Gallart et al., 2002) and the Ebro (López-Moreno et al., 2011) and Duero basins (Morán-Tejeda et al., 2012) in the Iberian Peninsula. Similar results have been reported in northwestern Anatolia (Albek et al., 2004) and southeastern France (Cosandey et al., 2005). In the Iberian Peninsula, trends toward higher frequency, duration and severity of hydrological droughts compared to the same characteristics for climatic droughts have also been registered, suggesting an increasing role for vegetation in hydrological control (Peña-Angulo et al., 2021).

Land cover also has a great impact on flood control and implications for flood risk management. Varied responses to extreme precipitation events were observed depending on the extent and density of vegetation cover (Lana-Renault et al., 2014), with longer runoff response times in more densely vegetated catchments, and very short responses with very steep rising limbs of the hydrographs (potentially catastrophic) in sparsely vegetated catchments

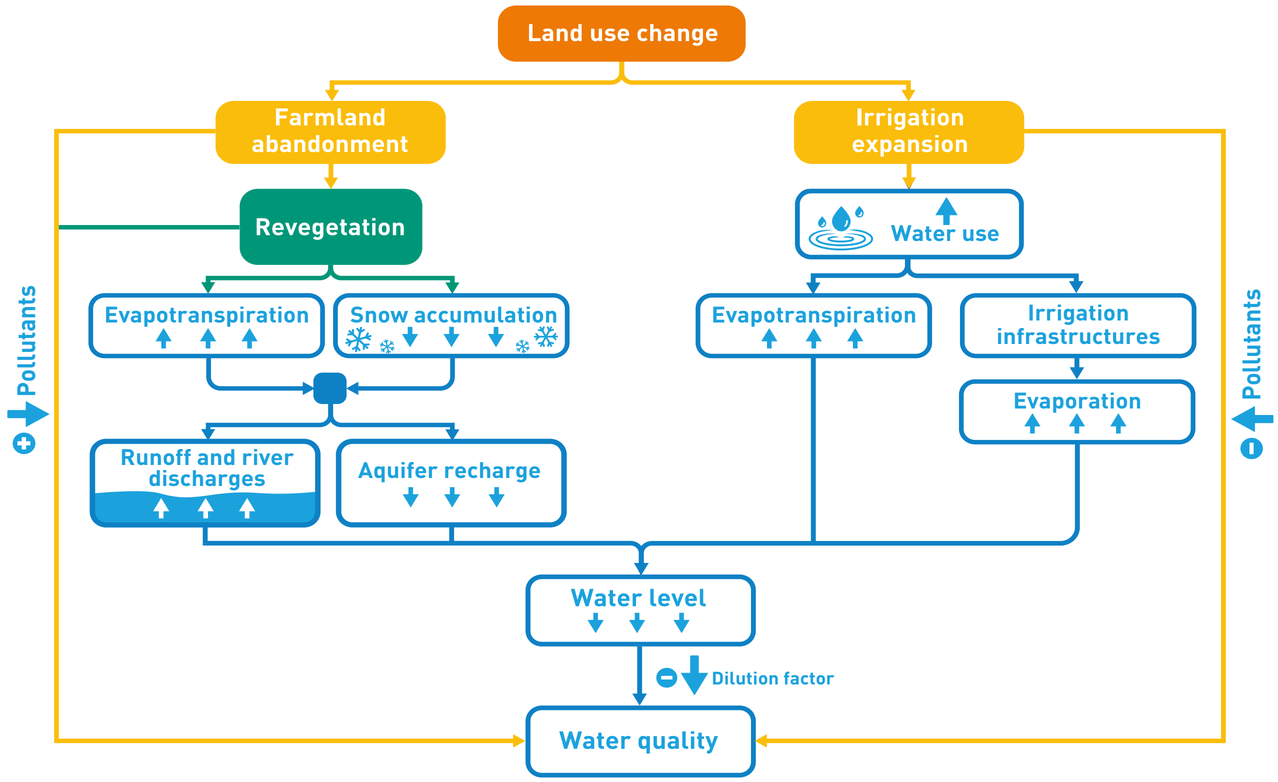

Figure 2.5 | Main impacts of land use change on water availability and quality in the Mediterranean region. Up and down arrows indicate an increase and a decrease, respectively. The symbols + and – represent a positive and negative impact, respectively.

(Camarasa-Belmonte, 2016; Delrieu et al., 2005; Lorenzo-Lacruz et al., 2019; Ortega & Garzón-Heydt, 2009).

In mountainous Mediterranean areas, where snow accumulation during winter plays a vital role for water availability during the dry season in the lowlands, it has been observed that forests reduce beneath-canopy snow accumulation (Lundquist et al., 2013), resulting in the reduction of the annual peak of snow-water equivalent and leading to earlier snowmelt (López-Moreno & Latron, 2008; Revuelto et al., 2016).

Increased irrigation is another LULCC responsible for large-scale impacts on water availability, since irrigation agriculture is the most water-demanding economic sector in the Mediterranean region (Lana-Renault et al., 2020), and usually involves unsustainable land use practices (Fader et al., 2020). The rainfed to irrigation conversion usually involves a change to higher market value crops with greater water requirements, like vegetables and orchards in Türkiye (Tanrivermis, 2003), or vegetables and citrus fruits in Morocco and Spain (Bekkar et al., 2007). Moreover, more frequent and abundant water supply is significantly increasing crop evapotranspiration (up to 20%) (Rodríguez-Díaz et al., 2011) and subsequent water consumption (Molle & Tanouti, 2017). The construction of huge reservoirs to feed irrigation produces greater water surface areas, causing increased evaporative losses (Martínez-Granados et al., 2011). Increasing demand for irrigated agriculture to stabilise market production and maintain food security exacerbates the general increase in water scarcity as a result of climate change (Iglesias et al., 2012). Depending on the warming scenario (2°C or 5°C), the need for irrigation in the Mediterranean is expected to rise by 4 to 18% by the end of the century. Increases of 22-74% are possible due to population growth and higher demand. However, it is not only the irrigated agriculture sector that is expected to increase its demand for an already strained resource. By the 2050s, industrial water demand in the Balkans and southern France is projected to increase by 50 to 100% (Forzieri et al., 2014).

The hydrological alterations caused by LULCCs are correlated with water quality (Stefanidis et al., 2016)

(*Figure 2.5*). Longer dry season flows concentrate contaminants, allowing the accumulation of detritus, algae, and plants, and fostering higher temperatures and lower dissolved oxygen levels (Cooper et al., 2013). Additionally, intensification of agricultural systems in recent decades in many Mediterranean areas has negative effects on water quality, particularly those associated with intensive and heavily irrigated and fertilised systems (Matono et al., 2019). In this regard, irrigated agriculture is one of the major diffuse sources of contamination of surface and groundwater bodies (mainly from pesticides and fertilisers) (Darwish et al., 2011; Martín-Queller et al., 2010; Re et al., 2014). A major issue for future decades is the multiplication of new contaminants from the active ingredients in agricultural products, which can be found in surface and groundwater bodies. The large number of these compounds, but also the cost of analyses, may explain the limited number of systematic surveys conducted (Leduc et al., 2017).

2.2.1.3 Population growth, urbanisation, industrialisation, lifestyle changes, war

Contrasting demographic trends have occurred in the Mediterranean region over recent decades (see *Section 2.2.1*), resulting in worsening of water security in northern Africa, where the greatest population growth has been seen. Moreover, both projected population growth and precipitation decrease will continue to threaten access to safe drinking water and availability for agricultural supply (Scheffran & Brauch, 2014). Inequalities in access to safe drinking water will likely occur in northern Africa, especially in Egypt and Morocco, where high water poverty indices caused by climate change have an impact on access to water as well as on social and economic life (Schilling et al., 2012). Nevertheless, Morocco has made significant efforts to improve water access, achieving 100% and 98% coverage in urban and rural areas, respectively, in 2021.

Population growth has led to rapid and intense urbanisation processes, especially in coastal areas (Cherif et al., 2020). The low-density urban sprawl model characteristic of northern countries has boosted water consumption. For example, in Barcelona, water consumption of single households is four times (100 l capita^{-1} day^{-1}) that of compact urban developments (multi-household residences) (March & Saurí, 2010). Water consumption is even higher for single houses with gardens or swimming pools, both common features of residential tourism (Hof & Schmitt, 2011; Rico-Amoros et al., 2009). Moreover, evaporative loss from swimming pools is not negligible (i.e. 4.8 hm^3 in 2015 in the Balearic Islands; Hof et al., 2018). Tourism alone is responsible for consuming 24% of total water resources in Mediterranean tourism hotspots (García et al., 2022). For example, in the Balearic Islands, water consumption in hotels ranged from 500 litres per guest and night in 3-star hotels to 700 litres in 5-star hotels (Deyà Tortella & Tirado, 2011). In Morocco, differences between hotel categories are similar, although the overall consumption is considerably lower (300 litres per guest and night in 3-star hotels and 500 litres in 5-star hotels). Leisure infrastructure associated with this type of tourism model has led to proliferation of golf courses in many coastal areas of the Mediterranean region, especially in northern countries. In southern and eastern countries, both urbanisation and tourism growth are also expected to increase water demand (Lana-Renault et al., 2020). For instance, golf courses and tourist areas near Agadir (Morocco) are expected to double by 2030 (Choukr-Allah et al., 2016).

Changes in dietary patterns generate crop strategy shifts to satisfy the market's demand for non-native cereals (Vanham et al., 2016), vegetables and fruit varieties that result in higher irrigation water demand, also impacting water security (Bekkar et al., 2007; Tanrivermis, 2003). The current diet in most European Mediterranean countries is far from the recommended Mediterranean diet, and a shift towards it (smaller amounts of proteins and fats and richer in fibre and micronutrients) would reduce the consumptive water footprint. For example, in Spain, this shift could lead to a reduction of approximately 750 litres per capita per day, based on data from the 2014-2015 reference period (Blas et al., 2019).

War in the Mediterranean has severe implications for water availability and security. Armed conflicts often result in the destruction of vital water infrastructure, such as treatment plants and pipelines, leading to water scarcity and contamination, which in turn poses risks to clean drinking water access and worsens food and economic insecurities (World Bank, 2017). In a region with multiple riparian states sharing critical water bodies like the Nile and Jordan River, conflicts escalate tensions over water-sharing

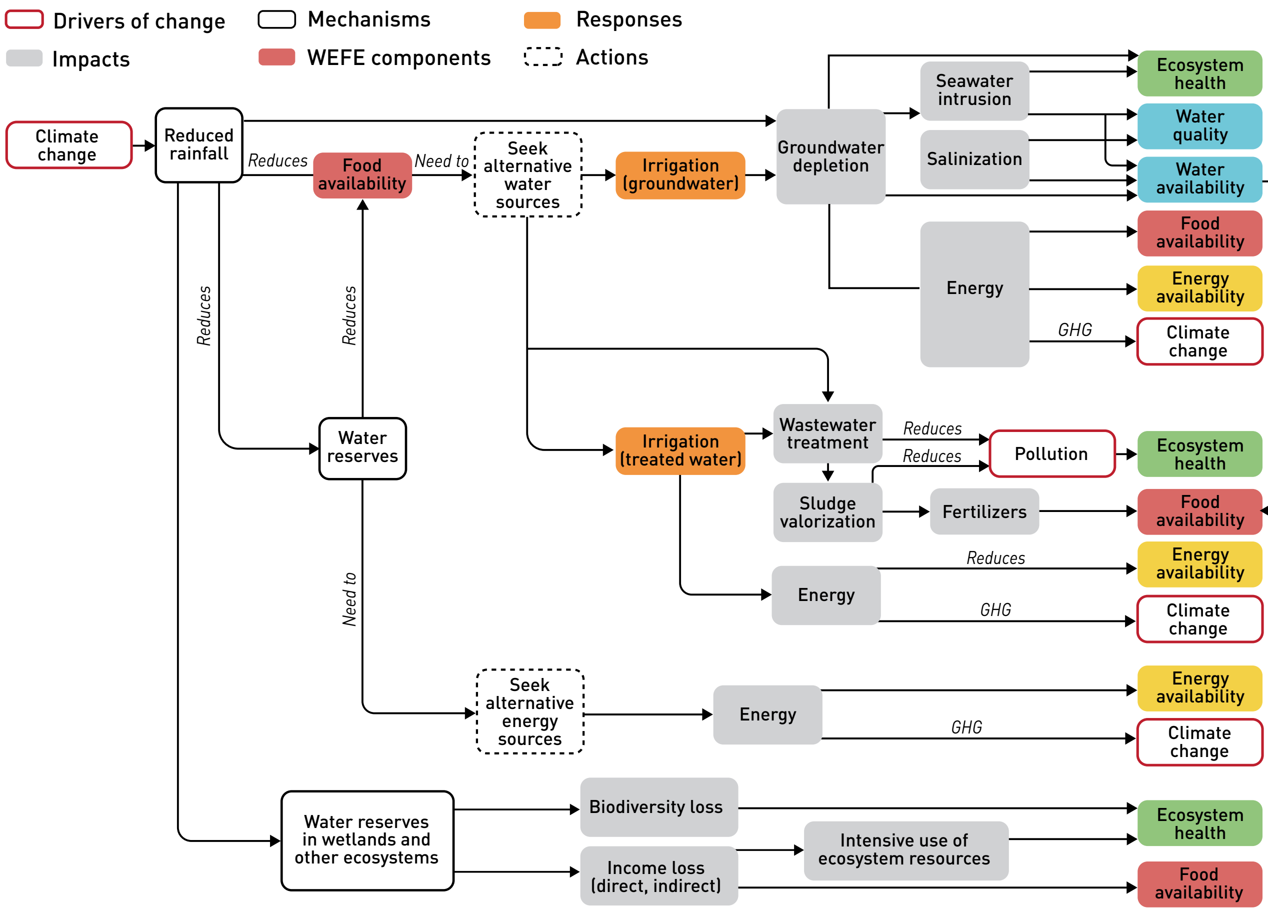

Figure 2.6 | Example of cascading impacts of climate-induced water changes on food, energy, and ecosystems.

agreements, potentially resulting in instability and disputes. Agriculture, being a major water consumer, suffers from war-induced disruptions, leading to crop failures and food shortages (Al-Muqdadi, 2022).

Population increases, particularly in coastal areas, and increasing urbanisation and dietary changes, also affect the quality of surface water and groundwater (high concentrations of nutrients, suspended solids, inorganic and organic chemicals, hydrocarbons, pesticides, heavy metals, potential endocrine disruptors, micro and nano plastics, microbial, etc.) (Chen et al., 2020; García-Nieto et al., 2018; Keshta et al., 2020; Papastergiadou et al., 2010; Salhi et al., 2021). In the Po River, the largest hydrological basin in Italy and the third tributary of the Mediterranean semi-enclosed basin, nutrient load projections for 2100 are strictly dependent on the resident population, which is responsible for a 61 and 41% increase for nitrogen and phosphorus, respectively (Copetti et al., 2013). Although sewage treatment plants play a crucial role in maintaining water quality, untreated wastewater discharges remain a challenge in the region (Llamas-Dios et al., 2021; Perrin et al., 2014). The Llobregat and Besós river basins (northeastern Spain) which supply water to the city of Barcelona, receive extensive urban, agricultural, and industrial wastewater discharges. Different studies have investigated the presence and effects of micropollutants, endocrine disruptors, metals and persistent organic pollutants in fish and invertebrates from these rivers (Barata et al., 2005; Fernandes et al., 2002; Solé et al., 2000; Teixidó et al., 2001).

2.2.2 Cascading impacts of climate-induced water changes on food, energy, and ecosystems

Climate change exacerbates the difference between water demand and the limited availability of renewable water resources, especially for countries located in the south and east of the Mediterranean Basin with a growing economy and population (Cramer et al., 2018;

Tramblay et al., 2020b). The effects of climate change in terms of reduced precipitation and frequent droughts have very negative effects on the availability of water resources, but this effect will cascade, through a series of interactions, onto the other WEFE nexus components (*Figure 2.6*).

Climate change impacts rainfall variability and infiltration rates directly affect groundwater recharge and water quality (Al Atawneh et al., 2021; Barbieri et al., 2023; Green et al., 2011). In countries with arid and semi-arid climates, groundwater resources are used more intensively to supplement water use in water supply and irrigation as an adaptation measure to climate-induced water scarcity (Iglesias et al., 2007; Kuper et al., 2017), leading, over an extended period of time, to a drop in groundwater levels in the Mediterranean (Hssaisoune et al., 2020; Schilling et al., 2020; Xanke & Liesch, 2022) (*Figure 2.7*). This, in turn, results, in the long term, in higher pumping water costs which can in turn reduce crop yields (Aw-Hassan et al., 2014). The reduction of the supply of local crops can lead to a higher demand for crops, hence affecting agricultural commodity prices and jeopardising food security (Dalin et al., 2019).

In addition, the consumption of non-renewable energy for irrigation leads to increased GHG emissions and carbon footprint in agricultural production (Daccache et al., 2014). In the case of some vulnerable environments, declining groundwater resources may also lead to a loss of ecosystem services (Bangash et al., 2013; Terrado et al., 2014). This vicious circle can be observed, for example, in the case of oasis ecosystems in southern Mediterranean countries, which have been strongly affected by climate change (Haj-Amor et al., 2020).

The decrease in aquifer recharge could also affect water quality, as a low recharge rate leads to an increase in water salinity (Hssaisoune et al., 2020; Mastrocicco et al., 2021; Velis et al., 2017), which can limit water uses, including in ecosystem services (Kath et al., 2015). In the case of coastal aquifers, overexploitation of groundwater can cause saltwater intrusion, which has even more negative consequences on water quality and can make resources unusable for irrigation and domestic use. Farmers are then compelled to abandon their wells, thus significantly reducing agricultural production (Agoubi, 2021; de Filippis et al., 2016; Mastrocicco & Colombani, 2021; Mazi et al., 2014). Saltwater intrusion can also be caused or exacerbated by sea level rise, another impact of climate change (Pisinaras et al., 2021; Sefelnasr & Sherif, 2014).

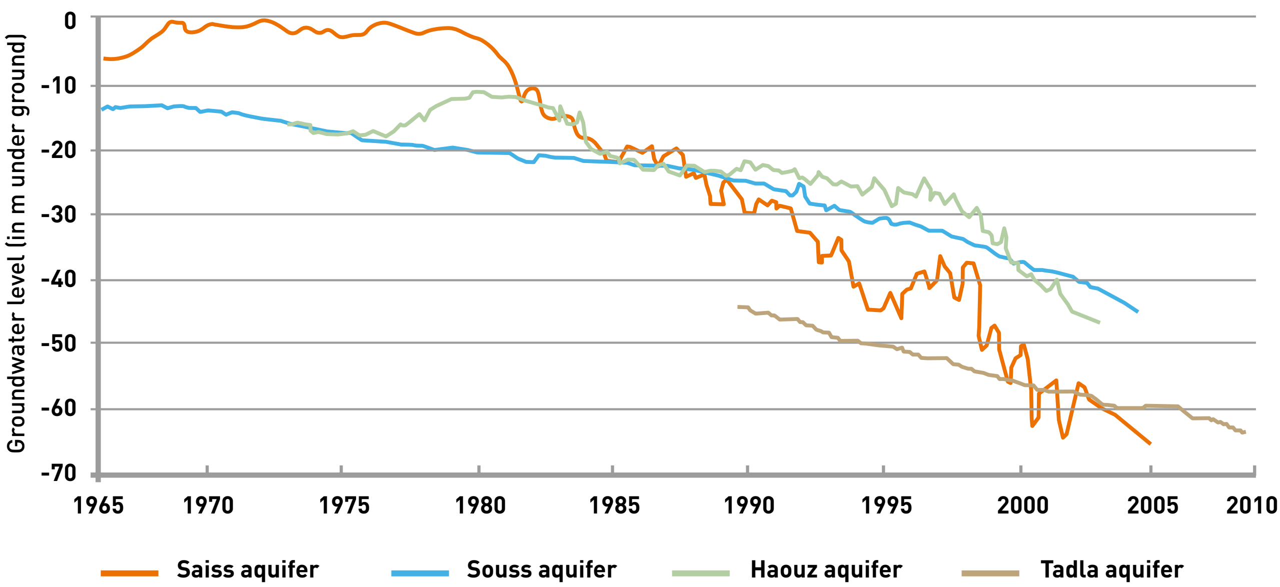

Figure 2.7 | Decline of groundwater levels in some important aquifers in Morocco.
Source: Hssaisoune et al. (2020).

In many Mediterranean countries a significant portion of the national energy mix is provided by hydropower plants that depend on water flows in rivers. Climate impacts on decreasing water availability – and altered periods of water availability – will cause hydropower plants to reduce their electricity production and affect their efficiency (Turner et al., 2017), which will also affect electricity prices (van Vliet et al., 2013) and thus, energy security. Water availability for hydropower generation is further threatened by the expected increase in extreme events such as droughts and heatwaves, and by competition from the agricultural sector (Fortes et al., 2022). Climate impacts on water availability can have other significant effects on the energy sector, especially in cooling and the production of steam in thermal power plants, and in cooling for nuclear power plants. According to IAEA (2022), 87% of global electricity generated from thermal, nuclear, and hydroelectric systems directly depended on water availability in the year 2020. Moreover, the IEA (2021) indicates that one-third of thermal power plants that rely on freshwater availability for cooling are located in areas of high water stress. This is also the case for 15% of existing nuclear power plants, a share that is expected to increase to 25% in the next 20 years. Furthermore, 11% of hydroelectric capacity is also located in areas of high water stress. Approximately 26% of existing hydropower dams and 23% of projected dams are in river basins that currently have a medium to very high risk of water scarcity. Looking at the Mediterranean region, the IEA analysis suggests that most oil refineries and thermal power plants are located in areas of high water stress.

The Mediterranean Basin is recognised as a freshwater biodiversity hotspot (Filipe et al., 2013), and inland waters, such as wetlands and riparian ecosystems, are among the most biodiverse areas in the Mediterranean, and play a key role in the global carbon budget. They also provide a wide range of ecosystem goods (e.g. food, drinking water) and services (e.g. water purification, climate regulation, flood regulation, coastal protection, etc.), which greatly benefit human well-being. The functionality of these systems relies heavily on water levels, and any alterations in the hydrological cycle, as a result of climate change, can significantly impact their structure and operation (Zaimes, 2020). Under future climate change projections, the Mediterranean Basin is one of the most vulnerable sites in this regard (Lefebvre et al., 2019; Xi et al., 2021). Climate change-related impacts on water reserves in wetlands and riparian ecosystems can lead to significant biodiversity loss, among other effects (*Figure 2.6*). The effects induced by water changes will lead to the worsening of ecological conditions, particularly for aquatic biota. They are sensitive to changes in water level, water quality, and disturbances. An increase in drought frequency is expected to affect inland water characteristics, and therefore reduce their suitability for aquatic biota. Additionally, inland waters represent isolated environments, limiting their ability to explore new habitats during unfavourable environmental conditions (Carosi, 2022). Changes in the hydrological cycle from climate change can also cause habitat loss for rich and dynamic riparian plant communities, which differ and are more diverse than those of temperate riparian areas (Zaimes, 2020). Mediterranean wetlands are also important migratory corridors and foraging hotspots. However, if water reserves decrease, it could severely damage the flyways between Africa and Eurasia, putting vulnerable waterbird populations at risk of decline during long-distance migration (Xi et al., 2021). The adverse effects on the goods and services provided by inland waters from reducing water reserves may also lead to potential loss of income. For instance, the tourism sector may suffer from such impacts (Molina-Navarro et al., 2014), and fishing and other related food provision sectors may also be adversely affected by the alteration of these fragile ecosystems.

2.3 The WEFE cascade from the food change perspective

Growing food demand linked to population growth and lifestyle changes (e.g. dietary change), under the combined pressure of climate change and urbanisation, increases dependency on food imports, making people more vulnerable to food prices. International trade largely contributes to food security in the Middle East and North African countries (Baer-Nawrocka & Sadowski, 2019). There are substantial differences in terms of food security between Southern Europe and North Africa. In both cases there are significant examples of very intensive agricultural systems but, in the latter case, agroecosystems are highly limited by the Sahara, leading to heavy exploitation of agricultural lands. Yet, contextual factors, such as population size, land area, employment in agriculture and precipitation,

Country	Land area (million sq km)	% Agricultural land (2018)	% Forest land (2018)	Agriculture (% of gross value added in 2020)	Employment in agriculture (in 2020)	Mean precipitation (mm yr^{-1} 1986-2016)	Population size (million people in 2020)	Human development index rank (2020)
Algeria	2.381	17.4	0.8	12.4	9.7	82	44	91
Egypt	1.002	3.9	0.1	11.5	23.3	31	102	116
France	0.551	52.3	31.2	1.8	2.4	839	65	26
Italy	0.302	41.7	31.8	2.2	3.6	914	60	29
Lebanon	0.01	64.3	13.9	3.3	13.4	536	6.8	92
Libya	1.676	8.7	0.1	0.9	18.8	42	6.9	105
Morocco	0.447	67.4	12.8	13.9	34.1	302	37	121
Spain	0.506	52.4	37.2	3.1	4.0	597	47	25
Syria	0.185	75.8	2.8	20.6	10.5	275	18	151
Tunisia	0.164	62.7	4.5	10.4	12.7	266	12	95

Table 2.1 | Examples of socio-economic and agronomic characteristics for some Mediterranean countries that can determine actions for food security.
Source: Bioversity International (2022).

need to be considered when assessing the capacity of countries to develop actions for food security (*Table 2.1*).

2.3.1 Impacts of drivers of change on food security

2.3.1.1 Climate change

Overall, climate change poses threats to food security in the Mediterranean region through impacts on food availability, access, and quality (*Figure 2.8*). It is expected that these pressures will be different across the region and its production sectors, creating further regional imbalances (Mrabet et al., 2020). In most Mediterranean countries, agricultural lands are arid and semi-arid, and crop productivity is highly susceptible to climate change. Climate change, and other stress factors, will likely decrease agricultural production (crops, fish, and livestock) in many areas due to reduced water availability and heat stress, making the region sensitive to food imports (Scheffran, 2020). A 17% reduction in agricultural productivity is expected in the Mediterranean (Mrabet et al., 2020), down to 9% in Southern Europe, taking into account autonomous adaptation actions (Kebede et al., 2021). Climate change also causes irregularities in the raw materials supply chain for crop production, leading to economic uncertainty and social insecurity (Petrović et al., 2023). In the Delta region in Egypt, extreme hydrological events like sea level rise caused by climate change may negatively affect crops and animals and cause deterioration of arable land productivity. These impacts will also be triggered by extreme weather events in the form of unexpected changes in the seasonality of temperature and precipitation, that affect the seasonality of crops.

With regard to crops, drought, heatwaves, frost or heavy rainfall during critical phenological stages may bring unexpected losses due to crop diseases, yield reductions and increased yield variability (Cramer et al., 2018) for many crops. Warming, associated changes in the phenological cycle, heat stress around flowering, and a lack of chilling accumulation, together with a change to pest infestation risks and increased risk of diseases will affect olives, grapevines, and fruit trees (Ponti et al., 2014). Yield losses in the Mediterranean region are projected at 5.4% for grapes, 14.9% for olives and 27.2% for almonds under a relatively hot and dry scenario (by 2041–2070) (Bezner Kerr et al., 2022). Fruit quality for high-quality wines will also be impacted (Cardell et al., 2019; Fraga et al., 2016, 2020a; Lazoglou et al., 2018; Resco et al., 2016). Furthermore, decreased yield in cereals is caused by inadequate precipitation that affects plant development and shortens the grain-filling period (Özdoğan, 2011) (*Table 2.2*). For vegetables such as tomatoes, projected yield reductions by 2050 vary between 18 and 81% depending on the availability of water for irrigation (Saadi et al., 2015). However, climate change can also have positive yield impacts for particular crops in some areas (e.g. wheat in Sardinia, Bassu et al., 2009). Sea level rise, combined with land subsidence, may significantly reduce the area available for agriculture in some areas, especially in productive delta regions such as the Nile delta (Link et al., 2013). The critical role played by agrobiodiversity in ensuring food is also threatened by climate change, especially in arid and semi-arid areas. Agrobiodiversity destabilisation by climate change affects plants, animals, and microorganisms used for food and other ecosystem services. Mycotoxins can also impact food availability and quality (Medina et al., 2017). The emerging issue of potential aflatoxin contamination of corn, almond, and pistachio crops is occurring in areas of Southern Europe due to the subtropical climate (EFSA, 2008). A shift in traditional occurrence areas for aflatoxins is to be expected, with more prevalent contamination during heatwaves and drought, which may stress the host plant, facilitating infection and leading to potential food safety issues in the Mediterranean (Battilani et al., 2016; Moretti et al., 2019).

For livestock production, impacts depend on whether the production system is intensive or extensive (Rivera-Ferre et al., 2016). Intensive farming systems will be mostly impacted by a decrease in feed crop availability or impacts on infrastructure and animal buildings. Extensive systems will suffer from a reduction of pasture, heat stress, fertility rates, etc. (Bezner Kerr et al., 2022). The magnitude of impacts depends on animal species, breeds, geographical location, and adaptive capacity. Goats, and particularly dairy farming based on indigenous breeds, are less affected by heat stress associated with climate change (Silanikove & Koluman (Darcan), 2015). Generally, direct impacts on animals arise from changes in behaviour, physiology, and health. Indirect impacts are due to lower feed quality and availability, and inappropriate feed composition. By 2050, the abundance and distribution of palatable plant species for grazing animals will be reduced due to climate change and increased grazing pressure (Louhaichi et al., 2019). Generally, besides decreased appetite, extreme heat stress reduces digestion efficiency and assimilation of feed and therefore leads to reduced growth rates, beef, milk, and egg production (Goma & Phillips, 2022). Overall, heat stress alters production and reproduction performance for all animal species, irrespective of the breed and production system. Local breeds are more adapted to heat stress than pure breeds, but they are nevertheless sensitive to it. In dairy animals, an increase in the temperature-humidity index of one unit over 69 decreases milk production by 0.41 kg per cow per day (Goma & Phillips, 2021). Heat stress also negatively impacts milk quality (Yerou et al., 2019). Key milk quality attributes significantly reduced by heat stress include protein content, butyrate, and total dry matter (Bernabucci et al., 2014). Moreover, extreme temperatures alternate the estrus cycle and may cause premature parturition (Goma & Phillips, 2022) and death in situations where animals fail to tolerate heat. In Syria, climate change caused a reduction of goat and sheep herds from −3.3 to −9.0% annually between 1999 and 2001 (Breisinger et al., 2011). By contrast, in other countries like Algeria, climate change could facilitate the expansion of farming alternative species, such as camels (Boudalia et al., 2023).

Oceans and Mediterranean Sea warming and acidification are among the most important factors impacting fisheries, with more than 20% of exploited fish and marine invertebrates expected to become locally extinct around 2050 in the Eastern Mediterranean due to climate change (Cramer et al., 2018). Projections for 2041–2060 are that 25 species would qualify for the International Union for the Conservation of Nature and Natural Resources (IUCN) Red List, and six species would be extinct. By 2070–2099, 45 species are expected to qualify for the IUCN Red List whereas 14 are expected to be extinct (Ben Rais Lasram et al., 2010). Changes in temperature have reduced fishery landings (on average by 44%) for around 70% of the 59 most abundant commercial fish between 1985 and 2008, although increases were also found – mostly for species with short lifespans. For six out of eight of the fish species examined, catch per unit of effort is correlated with temperature (Tzanatos et al., 2014). In Türkiye, the fishing sector's high sensitivity to climatic stressors (temperature and storms) negatively affected its economic performance between 2018 and 2019. The rise in sea level and sea temperature affected survival

Crop	Region/Country	Yield variation (%)	Period	Climate scenario	Reference
Barley	Mediterranean Basin	-27 (dry scenario) to +8 (wet scenario)	2050	RCP4.5	Cammarano et al. (2019)
Maize	Egypt	-19 to -14 -40 to -47	2050	SRES scenarios 1.5°C rise in the future	EEAA (2016) Ouda & Zohry (2020)
	Portugal	-17	2061-2080	RCP8.5	Yang et al., (2017)
Olive	Mediterranean Basin	-28 to +36 -14 to +70	2071-2100	RCP4.5 RCP8.5	Mairech et al. (2021)
	Southern Europe	-17 to +4 -20 to +3	2041-2070 2041-2070	RCP4.5 RCP8.5	Fraga et al. (2020b)
Potato	Egypt	-11 to -2 -11 to -13	2050	SRES scenarios 1.5–3.5°C rise in the future	EEAA (2016) Ouda & Zohry (2020)
Rice	Egypt	-11 -26 to -47	2050	SRES scenarios 1.5°C rise in the future	EEAA (2016) Ouda & Zohry (2020)
	France	-6 to -5	2030, 2070	RCP2.6	Bregaglio et al. (2017)
	Italy	-20 to -12		RCP8.5	
Sunflower	Southern Spain	-80 to -10 -12	2070, 2100 2050	A1B	Abd-Elmabod et al. (2020)
Tomato	Egypt	-19	2050	SRES scenarios	Ouda & Zohry (2020)
	Italy	-9 -26	2030-2059 2070-2099	A2	Ventrella et al. (2012)
Vineyard	Mediterranean Basin	-11 to +4	2021-2050	SRES A1B	Ferrise et al. (2016)
	Southern France	-20 to +2	2031-2060 2071-2100	RCP4.5 RCP8.5	Naulleau et al. (2022)
Wheat	Egypt	-18 -11 to -12 -27 to -31	2050	SRES scenarios 1.5°C–3.5°C rise in the future	EEAA (2016) Ouda & Zohry (2020)
	Italy	+11 -8	2030-2059 2070-2099	A2	Ventrella et al. (2012)
	Portugal	-14 -27 to -17	2021-2050 2051-2080	RCP4.5 RCP8.5	Yang et al. (2019)
	Türkiye	-35 to -3	2030, 2050, 2070	SRES	Özdoğan (2011)

Table 2.2 | Expected yield variation of certain crops in the Mediterranean under future climate scenarios.

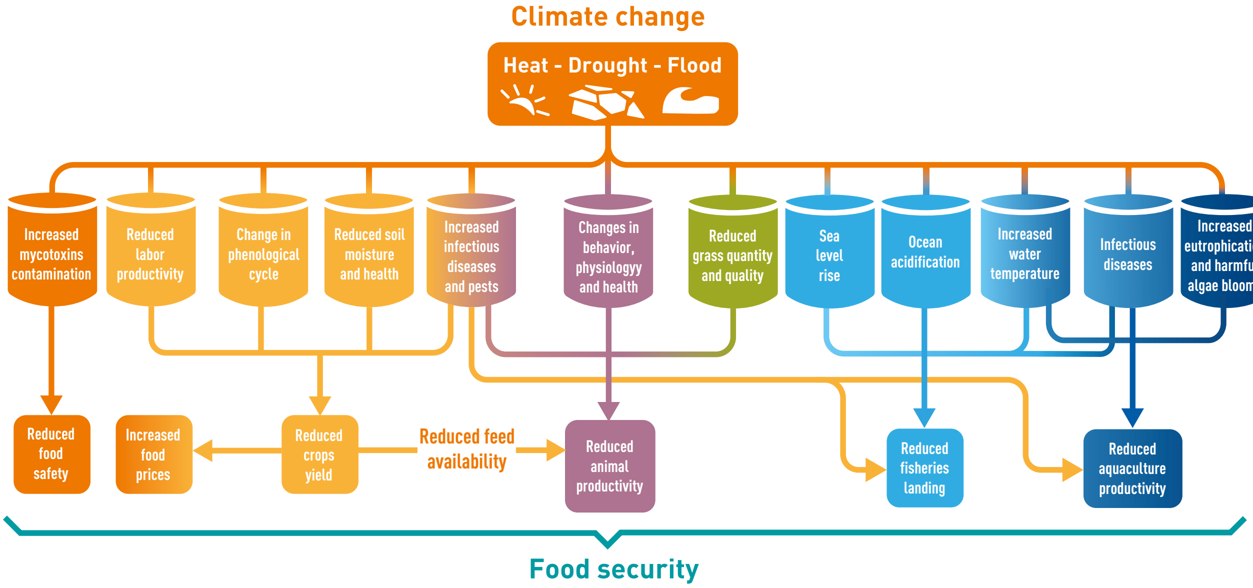

Figure 2.8 | Main impacts of climate change on food security.

of marine species (Gómez Murciano et al., 2021). In Italy, however, the temporal dynamics of total landings seem mostly driven by changes in fishing effort rather than by climatic factors (Fortibuoni et al., 2015), which illustrates the complex interactions in place between climate change and fishing effort.

Climate change is expected to impact aquaculture through an increase in temperature, eutrophication and harmful algae blooms, extreme events and water stress, sea level rise, acidification, and bacterial, viral, and parasitic fish diseases. Impacts of warming on aquaculture will depend on the production system, farmed species and country/region (Rosa et al., 2012). Disease outbreaks for the three main fish species farmed in the Mediterranean are expected to increase due to higher water temperatures (Cascarano et al., 2021) (*Figure 2.8*).

Climate change is projected to also have severe impacts on rural livelihoods and farmers across the entire Mediterranean Basin. In the MENA region, it is estimated that rural livelihoods dependent on (declining) agricultural productivity will likely continue to contribute to migration flows, often to urban areas, and will also increase import dependency and therefore vulnerability to agricultural impacts well beyond country borders (Kjellstrom et al., 2009; Waha et al., 2017). Also, migration resulting in loss of agricultural labour could heavily impact exploitation of female labour in some countries of the Mediterranean Basin, both in the South (Medland, 2021) and in the North (Corrado et al., 2017). In Tunisia, the incapacity of farmers to adapt their cropping systems to soil salinity and water stress saw income drop by 45% (Souissi et al., 2018). In Morocco, climate change leads to recurrent and extreme droughts causing social inequality due to loss of animals and fodder, since pastoralism provides 38% of the jobs to the community (Schilling et al., 2012). Changes in temperature, together with other variables such as humidity, wind speed and solar exposure, also influence heat stress and reduce labour productivity. This is particularly relevant for outdoor activities such as agriculture. In Mediterranean Europe, it is expected that in the 2080s there could be 50 to 60 additional days of heat leading to heat stress, with an average associated labour productivity loss of 3% (Szewczyk et al., 2021). Climate variability poses a "contingent liability" to the economy since it affects livestock survival and production of critical food security crops, and consequently affects the agricultural trade balance (Verner et al., 2018). The combination of crop yield and agricultural labour productivity losses due to heat stress is particularly severe in the MENA region, which is also particularly vulnerable to associated higher import prices (de Lima et al., 2021).

2.3.1.2 Pollution

Mediterranean food systems are seriously affected by air, soil, and water pollution. The Mediterranean Basin can be considered an air pollution hotspot in terms of decreased air quality. The most widespread pollutant in the Mediterranean region, and the most studied and damaging for crops is ozone (O_3) (Cotrozzi et al., 2018; Kalabokas et al., 2023). Nevertheless, the long-term monitoring of ozone impacts on crops has been limited because of their usual annual growth cycle. Exposure to high levels of tropospheric ozone can result in phytotoxic effects, affecting yields and product quality. As such, visible injury has been reported with several sensitive crop species, causing 17–39% yield loss in crops such as wheat, bean, watermelon, and tomato (Fumagalli et al., 2001; González-Fernández et al., 2014), and 0–20% commercial biomass loss in spinach and Swiss chard (González-Fernández et al., 2016). With regard to grapes, traditionally cultivated in the Mediterranean region, ozone exposure can affect both the yield and quality (Blanco-Ward et al., 2021). Nevertheless, it should be highlighted that the predicted effects based on a model may be overestimating impacts on Mediterranean environments since most physiological mechanisms activated upon ozone exposure, such as stomatal closure, often interact with those triggered by drought and hyperosmotic stress, which are typical of these environments (Fagnano et al., 2009). On the other hand, although the Mediterranean area is among the least studied regions in terms of the potential impacts of nitrogen (N) as a pollutant, there is growing concern that natural systems limited by N availability are being affected by enhanced N deposition from the atmosphere. Decoupling of the peaks of N availability derived from the solubilisation of summer-deposited N with the onset of autumnal rains and the peaks of nutrient demand by plants in the spring makes Mediterranean systems more vulnerable to indirect effects of N deposition (Cotrozzi et al., 2018). Finally, special attention should also be paid to potential contamination from heavy metals due to atmospheric pollution in high-traffic areas, since urban agriculture is on the rise (Ercilla-Montserrat et al., 2018). In any case, air pollution can not only affect plant growth but also shift the market equilibrium of both agro-inputs and -outputs, indirectly affecting food security (Sun et al., 2017).

Soil pollution is also extremely important. This can reduce crop yields due to toxic levels of contaminants and make foods unsuitable for human consumption (Rodríguez Eugenio et al., 2018). In particular, excess heavy metals (such as arsenic, cadmium, lead, and mercury) in soils can impair plant metabolism, decreasing crop productivity and affecting pasture, before entering the food chain and becoming a hazard (Boudebbouz et al., 2023; Zergui et al., 2023). Local soil properties mean that the Mediterranean area is very sensitive to cadmium accumulation (de Vries et al., 2022). Compared to metals, organic contaminants (such as dioxins, furans, and per- and polyfluoroalkyl substances (PFAS)) are less present in soils, localised around industrial or urban centres. Other important pollutants in soils are nutrients and pesticides, which, when applied in excess, negatively affect yields (Rodríguez Eugenio et al., 2018). In addition, pollution derived from solid waste could threaten food production and security by negatively affecting soil, groundwater and surface water and crops, leading to increased health concerns for livestock, aquatic life, and humans (Chen & Chen, 2021).

Water pollution has historically impacted food safety, and today, specific attention is paid to seafood contamination. Mediterranean marine ecosystems present an idiosyncratic combination of characteristics, which make them sensitive to pollution (e.g. high temperatures, microtidal regime, oligotrophy, coastal morphology, biodiversity, anthropogenic pressure, etc.). Sewage and oil still pose the most significant and obvious problems (Danovaro, 2003). Different types of priority contaminants (heavy metals, toxic metals, organophosphate esters, polychlorinated biphenyls, polybrominated diphenyl ethers and polycyclic aromatic hydrocarbons) have been found in several food species (swordfish, bluefin tuna, sardine, anchovy, sardinella, and European hake) around the Mediterranean Sea (Anastasopoulou & Fortibuoni, 2019; Bencheikh et al., 2022; Harmelin-Vivien et al., 2012; Sala et al., 2022; Signa et al., 2017; Storelli et al., 2005). Of the wide range of pollutants contaminating the aquatic environment, heavy metals have been a major focus, mainly mercury, lead, cadmium, and arsenic. Before the prohibition of industrial wastewater being drained into the Nile was strictly applied, arsenic was found at higher levels among people consuming fishes more than twice a week, as well as among smokers (Saad & Hassanien, 2001). As for mercury levels, of 58 different species for human consumption from the western Mediterranean Sea, only thirteen species do not exceed EU thresholds for human consumption (0.5 µg g^{-1} ww) (Capodiferro et al., 2022). On the other hand, it is well known that plastics, microplastics, and nanoplastics threaten marine life by physical damage but also by chemical pollution from the plastic additives (e.g. plasticisers, flame retardants and colour pigments) or other adsorbed chemicals (Schmidt et al., 2018). Microplastics, in particular, can pose risks by entering the food web (Gedik & Eryaşar, 2020). 41% of all fish collected along the Mediterranean coast of Türkiye have microplastic in their intestines and 58% in either stomach and/or intestines (Güven et al., 2017). Additionally, increasing evidence exists that emerging pollutants such as pharmaceuticals and endocrine–disrupting compounds can be bioaccumulated by aquatic organisms (Ruhí et al., 2016). Novel substances with biological activity may have synergistic effects with classical pollutants. Biomagnification patterns along the hake food web differ by contaminants due to their physicochemical properties (Harmelin–Vivien et al., 2012). Chronic exposure to multiple pollutants affects aquatic organisms, even at low concentrations, explaining the deterioration of fish health and fishery production decline along the Mediterranean coastline (Bencheikh et al., 2022). Nevertheless, the human health risk associated with consuming these fish species should be analysed for each compound and species, since some pollutants do not pose a significant threat to public health (Sala et al., 2022).

2.3.1.3 Population growth, urbanisation, industrialisation, lifestyle changes, war

The adoption of modern lifestyles in agriculture and food has also led to major transformations in traditional agriculture characterised by the promotion of agricultural industrialisation and international trade, and changes in diets involving more consumption of animal protein and ultra–processed food. In fact, food production and consumption patterns are amongst the vital drivers of environmental degradation (Capone et al., 2014) and agrobiodiversity deterioration in the Mediterranean.

Industrialisation, urbanisation, and demographic changes together with political and environmental drivers are the main factors for agricultural land use change in the Mediterranean (*Figure 2.9*). Social and demographic drivers are shown to be particularly relevant for abandonment, which is frequently associated with intensification processes. Intensification dynamics are driven mainly by economic factors, which particularly affect annual crop production (Debolini et al., 2018). The industrialisation of agriculture that occurred worldwide during the 20th century aimed at increasing agricultural production to ensure the supply of food to the increasing population and to increase agricultural trade worldwide. During this period, countries in the Mediterranean Basin increasingly specialised in Mediterranean agricultural products for export (Duarte et al., 2021). It also had negative consequences, destroying agricultural employment and causing a loss of profitability for agricultural activity, the overexploitation of hydric resources, water pollution by nitrates and pesticides, high erosion rates, losses of soil organic carbon and an alarming loss of biodiversity. In the immediate future, this damage is expected to end up reducing production capacity (Aguilera et al., 2018; González de Molina et al., 2020; Harchaoui & Chatzimpiros, 2019; Vila–Traver et al., 2021). The intense expansion of Mediterranean virtual water exports between 1910 and 2010 that accompanied the construction of water infrastructure and enabled water–intensive crops to be grown in arid regions has exacerbated blue water stress (Duarte et al., 2021). The fertiliser consumption indicator gives an idea of the level of intensification of agricultural production. In the period between 2002 and 2009, average fertiliser consumption in 21 Mediterranean countries was 188 kg ha^{-1}, higher than the worldwide average (116 kg ha^{-1} of arable land). Over the same period, average fertiliser consumption in the MENA countries (91 kg ha^{-1}) was lower than the level of fertiliser consumption in the Mediterranean Euro area (180 kg ha^{-1}) and Mediterranean EU countries (156 kg ha^{-1}) (Lacirignola et al., 2014).

In the Southern Mediterranean, industrialisation of agriculture has often been accompanied by the development of export agriculture. In Morocco, export–oriented and industrialised agriculture contributes to 15 to 20% of its Gross Domestic Product (GDP). This change has transformed the nature of labour in agriculture, with the marginalised rural population being contracted as wage labourers (Bouchelkha, 2016). In Algeria, the agricultural sector plays an important economic role: in 2020 it contributed to

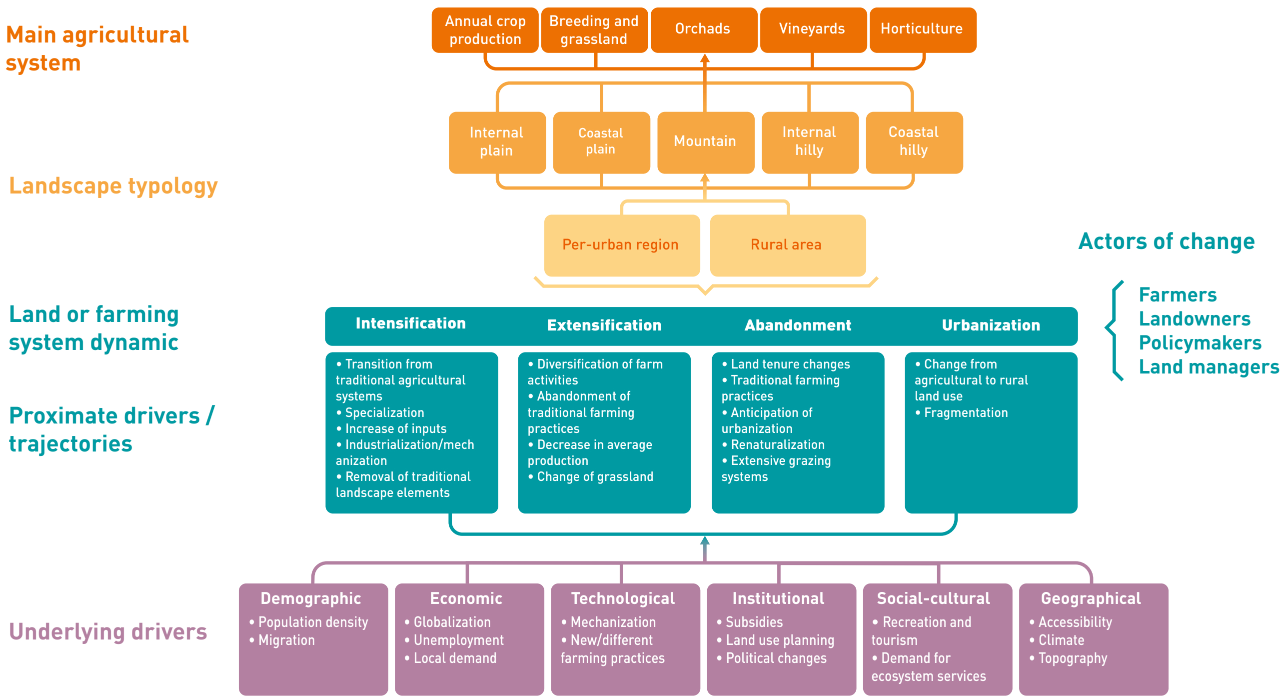

Figure 2.9 | Land and farming system dynamics in the Mediterranean.
Source: Debolini et al. (2018).

12.4% of the country's GDP and employed directly and indirectly around 13 million people. Yet, its agricultural area is prone to urban sprawl as a result of the growth of cities (Bellout et al., 2020).

Increasing urbanisation and industrialisation have also led to changes on the demand side, shifting food consumption patterns towards Western-style diets, characterised for being rich in energy and animal protein, and also linked to high levels of food waste. This nutrition transition has resulted in low adherence to the Mediterranean diet across the region (Grosso et al., 2014; Kyriacou et al., 2015; Marventano et al., 2018; Naja et al., 2019) with severe impacts on both human and ecosystem health. Dietary changes towards Western-style industrialised diets have been identified as drivers of the region's ecological deficit, including increased GHG emissions, changes in land use, energy use and water use. In Lebanon, dietary shifts towards diets with high environmental footprints among adolescents have been reported (Naja et al., 2020). An analysis of the ecological footprint (EFC) of consumed food in Mediterranean countries, i.e. the amount of land required to sustain their food consumption, showed the highest per capita values for Portugal, Malta and Greece (1.50, 1.25 and 1.22 global hectares (gha), respectively), while Slovenia, Egypt and Israel had the lowest (0.63, 0.64 and 0.79 gha, respectively). All in all, results show that all Mediterranean countries, except France, rely on the biocapacity of foreign countries to satisfy their residents' demand for food (Galli et al., 2017, *Figure 2.10*).

In general terms, the EFC in the Mediterranean is always higher than the EF of production, except for the case of Serbia (data for 2007; *Figure 2.11a*). Between 1961 and 2007, the ecological footprint per capita in the Mediterranean increased except in Albania, Jordan and Morocco, while biocapacity decreased, generating an ecological deficit. On average, the ecological footprint has increased by 47.4% while the biocapacity has decreased by 36.4%. The average ecological footprint in northern Mediterranean countries is at least 1.5 times the ecological footprint of MENA countries (Lacirignola et al., 2014, *Figure 2.11b*).

The Mediterranean food system is a traditional food system favoured by Mediterranean agroclimatic conditions, that involves commonly extensive, low-input farming, based on traditional knowledge

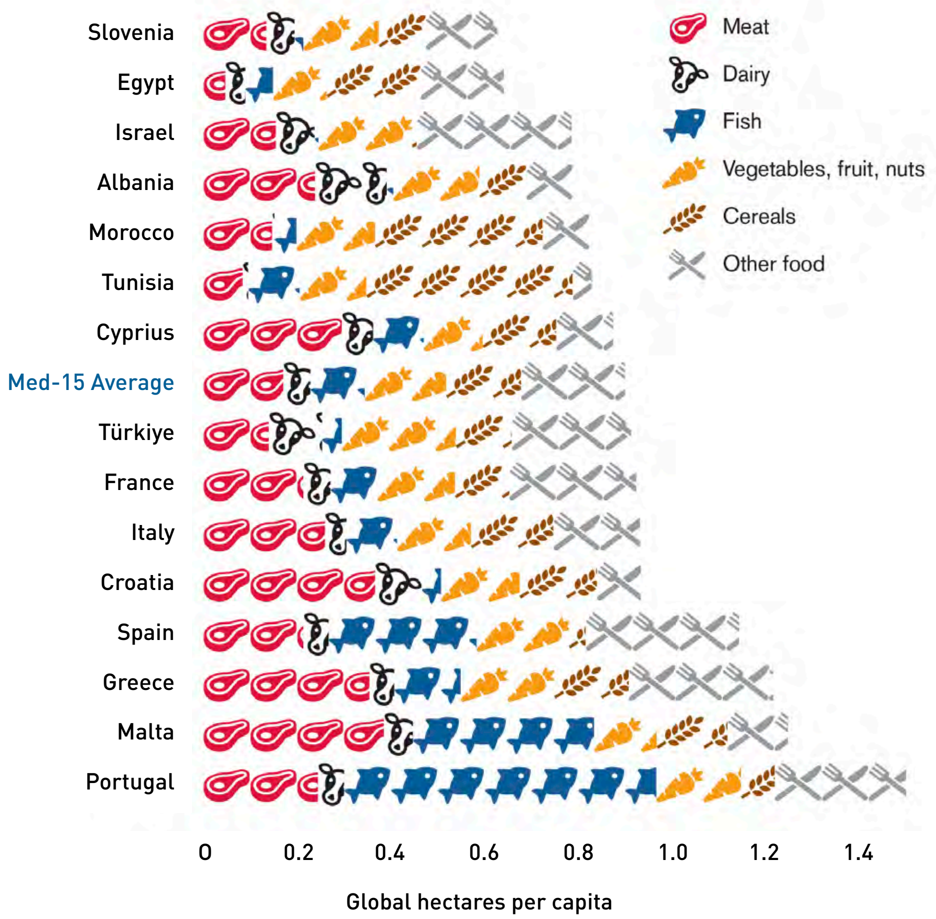

Figure 2.10 | Ecological footprint of per capita food consumption of Mediterranean countries in 2010, per type of food.
Source: Galli et al. (2017).

and using predominantly indigenous breeds, local crop varieties and wild foods. This has allowed the Mediterranean to be considered one of the world's eight "centres of origin", i.e. geographical areas where today's crops originated, and where, as a result, crop genetic diversity for wheats, barleys, forage plants, vegetables, fruits, spices, and ethereal oil plants, among others, is exceptionally high (Bioversity International, 2022). These plants have developed resilience traits that enable them to cope with the Mediterranean region's hot and dry summers. Agrobiodiversity Index status scores across ten Mediterranean countries as compared to global agrobiodiversity trends show that agrobiodiversity is well represented in some parts of Mediterranean food systems at the consumption level, indicating a high diversity of food contributing to healthy diets in markets and consumption. However, in production, the Mediterranean average is well below the global average, suggesting that production systems lack diversity (Bioversity International, 2022). Food systems in Mediterranean countries have undergone deep transformation away from the sustainable and healthy patterns that were predominant in the region until the mid–1960s. This transformation is evident across the whole food chain, from production to consumption, and has led to the erosion of a cultural heritage that maintained a sustainable balance between land and resource use, ecosystem conservation and healthy nutritional status. The industrialisation of agriculture and diets has significantly contributed to agrobiodiversity loss in the Mediterranean. Agricultural intensification has been shown to erode taxonomic and functional diversity in Mediterranean olive groves (Tarifa et al., 2021). Moreover, the erosion of Mediterranean food culture is accompanied by erosion of the plant and animal genetic diversity that characterises it, since the Mediterranean diet has also been linked with agrobiodiversity conservation (Renna et al., 2021). Agrobiodiversity loss from climate change, globalisation trends and urbanisation negatively

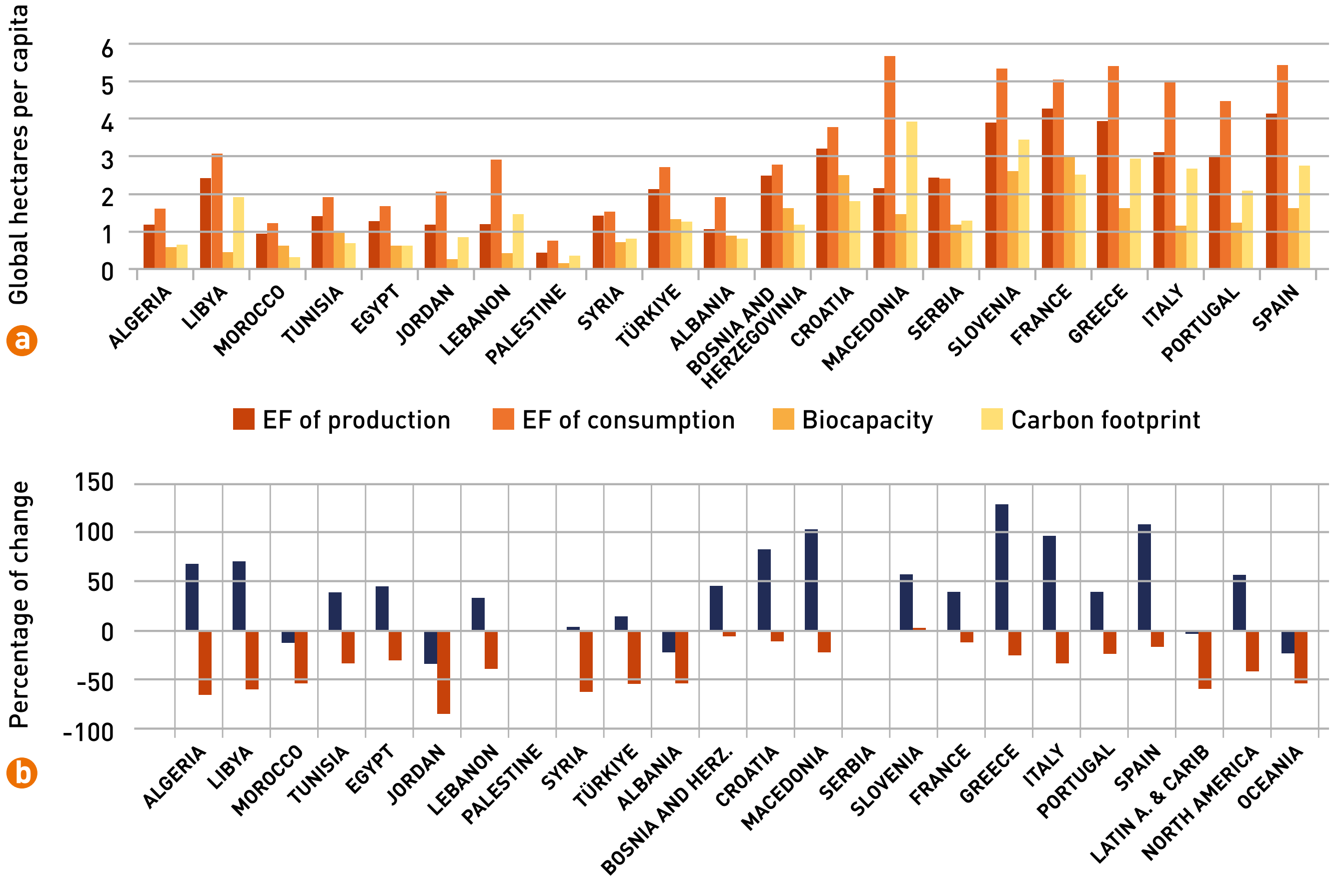

Figure 2.11 | a) Global hectares per capita (i.e. biocapacity), carbon footprint (CF) and ecological footprint (EF) of the production and consumption of food in the Mediterranean; b) Evolution of the EF and biocapacity in the Mediterranean countries from 1961 to 2007 (data shows change between 1992 and 2007).
Source: Lacirignola et al. (2014).

affects the livelihoods of populations inhabiting the region. Shrinking agrobiodiversity levels make farmers more vulnerable to climate risks in the Mediterranean, since less diversity in farming systems translates into reduced options for coping with change. Also, losing this diversity undermines the very survival of the Mediterranean diet and an opportunity to build a sustainable food system in the region. Transitioning back to the Mediterranean diet, including wild foods with high nutrition content, could contribute to counteracting the effects of climate change, malnutrition and biodiversity loss that are jeopardising food security in the region (Bioversity International, 2022; Borelli et al., 2022) (*Figure 2.12*).

Industrialisation of agriculture is also linked to increased food loss and waste. With regard to resources wasted associated to food loss and waste in the Mediterranean, Laricignola et al. (2014) estimated that from 294 (Palestinian territories) to 706 m^3 $capita^{-1}$ yr^{-1} (Portugal) of water is lost or wasted by Mediterranean people.

The war in Ukraine has had a clear impact on food availability and access across the Mediterranean, especially for those that rely on food imports, such as in the MENA region (Al-Saidi, 2023; Ben Hassen & El Bilali, 2022). In 2021, the Russian Federation and Ukraine together accounted for about 75% of the total wheat and wheat flour imports of Egypt and Lebanon, close to 40% in Tunisia, more than 30% in Jordan and around 20% in Morocco. In the southern and eastern Mediterranean group of countries, the proportion of imports to domestic availability of calories ranges from 37% (Morocco) to 84% (Jordan) (Rauschendorfer & Krivonos, 2022). The Russo-Ukrainian war impacts food security not only through disruption to food markets, but also to the

Figure 2.12 | Risks associated with low agro-biodiversity levels.

Source: modified from Bioversity International (2022).

fertiliser market, which may affect both food price and availability (Ben Hassen & El Bilali, 2022). The combined effects of war and climate change (e.g. droughts in Morocco) are also extremely relevant (Rauschendorfer & Krivonos, 2022). The climate–conflict link in Syria has also been examined for the 2006–2009 drought conceived of as a four-stage process, with various levels of scientific evidence and consensus existing for each stage: (1) climate change leading to the heavy 2006–2009 drought; (2) massive loss of agricultural livelihoods, significantly attributable to the drought; (3) massive rural-to-urban migration triggered by livelihood loss in combination with other factors; and (4) migration intensifying existing grievances and facilitating the onset of protests and the subsequent civil war (possible, but little knowledge exists) (Ide, 2018). Prolonged violence may also reduce the resilience capacity of households necessary to resist food insecurity, as observed in Gaza during the escalation of violence in 2014 (Brück et al., 2019). In that territory, the experience of food insecurity is associated with an approximate one-point reduction in dietary diversity as measured by food consumption score (Lin et al., 2022). The impact of the 2023 war on food security in the area cannot be assessed in this report due to lack of data at the time of the assessment. In sum, the high impact of war and conflicts on food security, combined with the significant dependence of many countries on food imports, unstable money exchange values, increasing trade uncertainty and future pandemics, is increasing the number of studies using a nexus approach to analyse the capability of countries to increase their food self-sufficiency, combining changes in food production and consumption, like Egypt (Fahim et al., 2013), France (Billen et al., 2018), Lebanon (Daher et al., 2022), Spain (Aguilera & Rivera Ferre, 2022), and South-East Europe (Brankov et al., 2021).

2.3.2 Cascading impacts of climate-induced food changes on water, energy and ecosystems

In the Mediterranean region, the effects of climate change are severely affecting the sustainable utilisation of resources to sustain human livelihoods. Climate change impacts on agricultural yield and therefore on food security, which can result in a series of cascading effects on other WEFE components, are mediated by the diversity of responses available to address the impacts of climate change (*Figure 2.13*). Cascading effects from food can be mediated by production (supply) and consumption (demand) trends. To produce food, agriculture requires indispensable resources like energy, soil, water, and then, of course, farmers. Food production also alters ecosystems, and it is expected to be the primary factor influencing Europe's future landscape changes (Kebede et al., 2021). The allocation of agricultural land and land use is frequently influenced by intricate cross-sectoral interactions that have cascading effects on other sectors, including forestry, biodiversity, energy, and water. Sustaining current levels of food production could be achievable under several climate and socio-economic scenarios, with strong impacts on biodiversity and water, particularly in Mediterranean Europe, where water stress is projected to increase by 26% in Southern Europe and 32% in Eastern Europe (Kebede et al., 2021). This raises questions about the long-

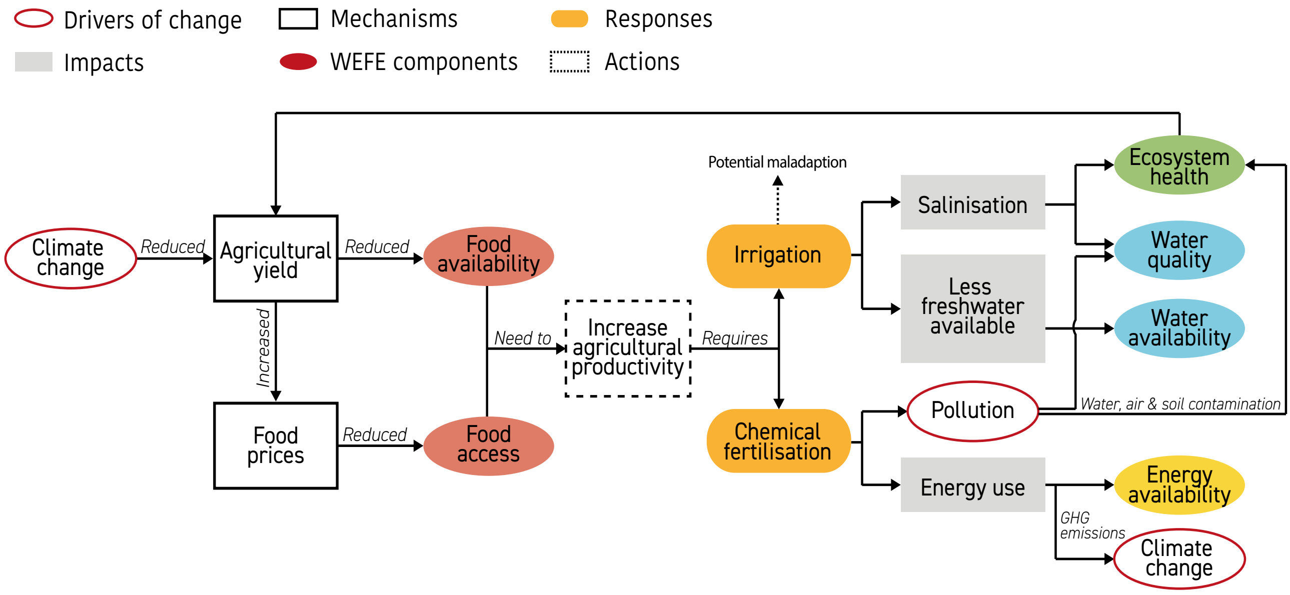

Figure 2.13 | Example of the negative cascading effects associated with climate-induced food security changes (access and availability) on water, energy, and ecosystems, initiated by the driving force "climate change" and followed by "business-as-usual" responses (see *Chapter 3*).

term sustainability of current production and consumption policies (Funes et al., 2021). Actions aimed at increasing agricultural yield through business-as-usual responses, such as increased irrigation or use of synthetic chemical fertilisers, can negatively impact water security, energy security and ecosystem health through a diversity of pathways. From a food perspective, reduced agricultural productivity due to climate change leads to an increase in water demand for irrigation, with impacts on water availability and ecosystem health through salinisation or changes in land use to expand the agricultural area and increase energy demand, also affecting ecosystems. In parts of Southern Europe, salinisation, which may result from drought and an increase in irrigation (see *Section 2.2.1*), is indeed a major problem. Soils in large areas of Spain and some regions of Greece and Italy are already salinised (Scheffran & Brauch, 2014). The degradation of ecosystems further affects soil quality and moisture, carbon cycle and local climate. Self-reinforcing consequences are lower air humidity and less precipitation. If this trend continues, it can lead to desertification, with land then being lost for future agricultural use (Scheffran & Brauch, 2014). In addition, agriculture depends on expensive external non-renewable energy inputs, which are imported. Currently, over 0.5 units of non-renewable energy produces a unit of crop energy. Moreover, in northern Mediterranean countries, the intensity of non-renewable energy is slowly declining (Aguilera et al., 2020). Increased food transportation to satisfy food security through imports raises energy demand and dependency, as well as GHG emissions. Globally, post-farm emissions contribute 5-10% of global GHG emissions (Mbow et al., 2019).

2.3.3 Cascading impacts of human-induced food changes on water, energy, and ecosystems

Cascading effects also arise from indirect drivers of change in food systems, such as population growth or lifestyle changes, and in particular, increased consumption of animal-based products associated with the promotion of industrialised systems (*Figure 2.14*). Production of large-scale industrial animal protein to satisfy current demand requires the cultivation of cereals and leguminous crops in third countries (Garrett & Rueda, 2019). Cultivation of feed crops for animal production in the Mediterranean is leading to deforestation in some countries in Latin America (Martínez-Valderrama et al., 2021). Deforestation increases CO_2 emissions, destroys ecosystems, and reduces

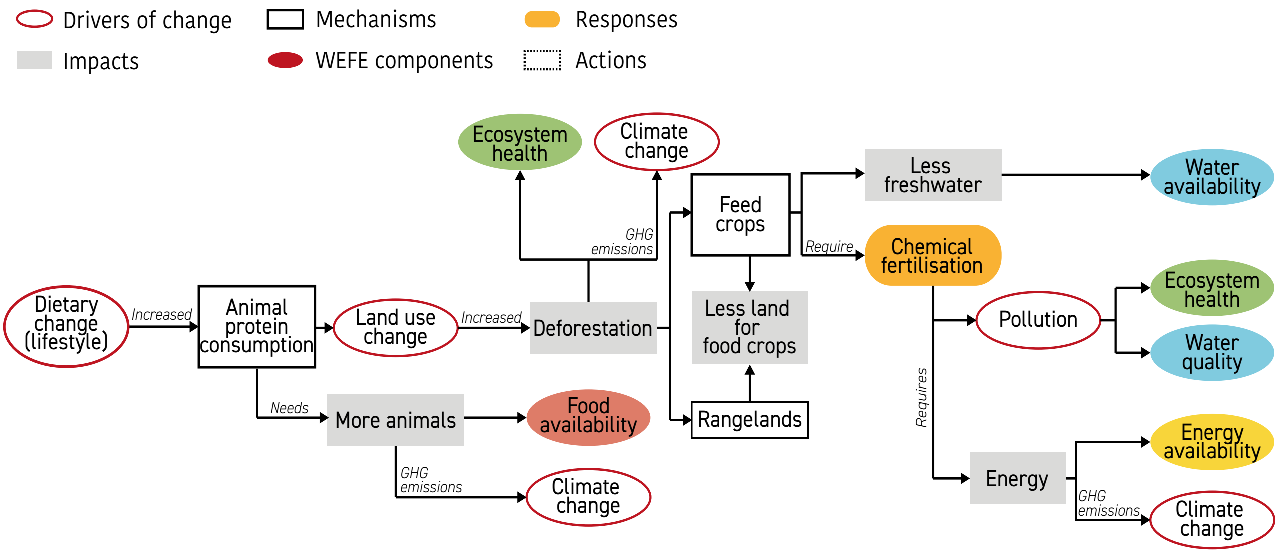

Figure 2.14 | Example of the negative cascading effects associated with lifestyle-induced food security changes on water, energy, and ecosystems, initiated by the driving force "dietary change" and followed by "business-as-usual" responses.

biodiversity. Deforestation also means less land for food crops for humans or alternative uses. For example, Spain's current food demand requires cultivation of 6 Mha in other countries, of which 5 Mha is for animal production (feed crops or pasture) (Aguilera & Rivera Ferre, 2022). In addition, the production of feed crops in deforested land has the same impacts on WEFE as those described above. Breeding more animals, particularly ruminants, also increases direct GHG emissions in the form of methane. With monogastric species, GHG emissions mainly occur indirectly, both upstream (e.g. production of feed) and downstream (e.g. through ammonia volatilised and further deposited). Furthermore, regions with over-abundant N have been identified in the region, mainly in EU countries where intensive livestock and cropping systems exist (e.g. Sanz-Cobena et al., 2023). Increasing amounts of reactive N entering these systems as N fertilisers and animal manures are triggering the emission of reactive N into the atmosphere, as well as into soil and water bodies, in the form of the air pollutant ammonia and oxides of N (NO_x and N_2O). Inefficient conversion of N in agroecosystems is making a significant contribution to this situation (Aguilera et al., 2021).

Box 2.1

Intensive livestock production systems and nitrogen cycle

On the basis of some intensive industrial farms in the Mediterranean, these farming systems, particularly for monogastric species, are characterised as:

- Being energy dependent
- Having external feedstock demand with a high energy cost (i.e. transport or synthetic fertiliser)
- Having enhanced reactive N losses into the environment – air (ammonia) and water pollution (nitrates) – with impacts on ecosystems
- Having increased GHG emissions, mostly indirect (upstream) due to land use change (impact on ecosystem health)

These livestock production systems are mostly focused on the export market (*Figure 2.15*). Nevertheless, they rely on (and support) an extended transition to unsustainable and unhealthy diets that has been occurring over the last four decades in Mediterranean countries, far removed from more "territorially appropriate" eating habits (e.g. Mediterranean diet).

Livestock systems sustained on imported feedstock/livestock are responsible for disrupting local and regional nitrogen cycles, thus triggering environmental losses in the form of ammonia (to the atmosphere) and nitrates (to surface and groundwater) (*Figures 2.15* and *2.16*). These reactive N losses are the result of high inefficiency in the use of nitrogen and are behind relevant impacts linked to both human and ecosystem health.

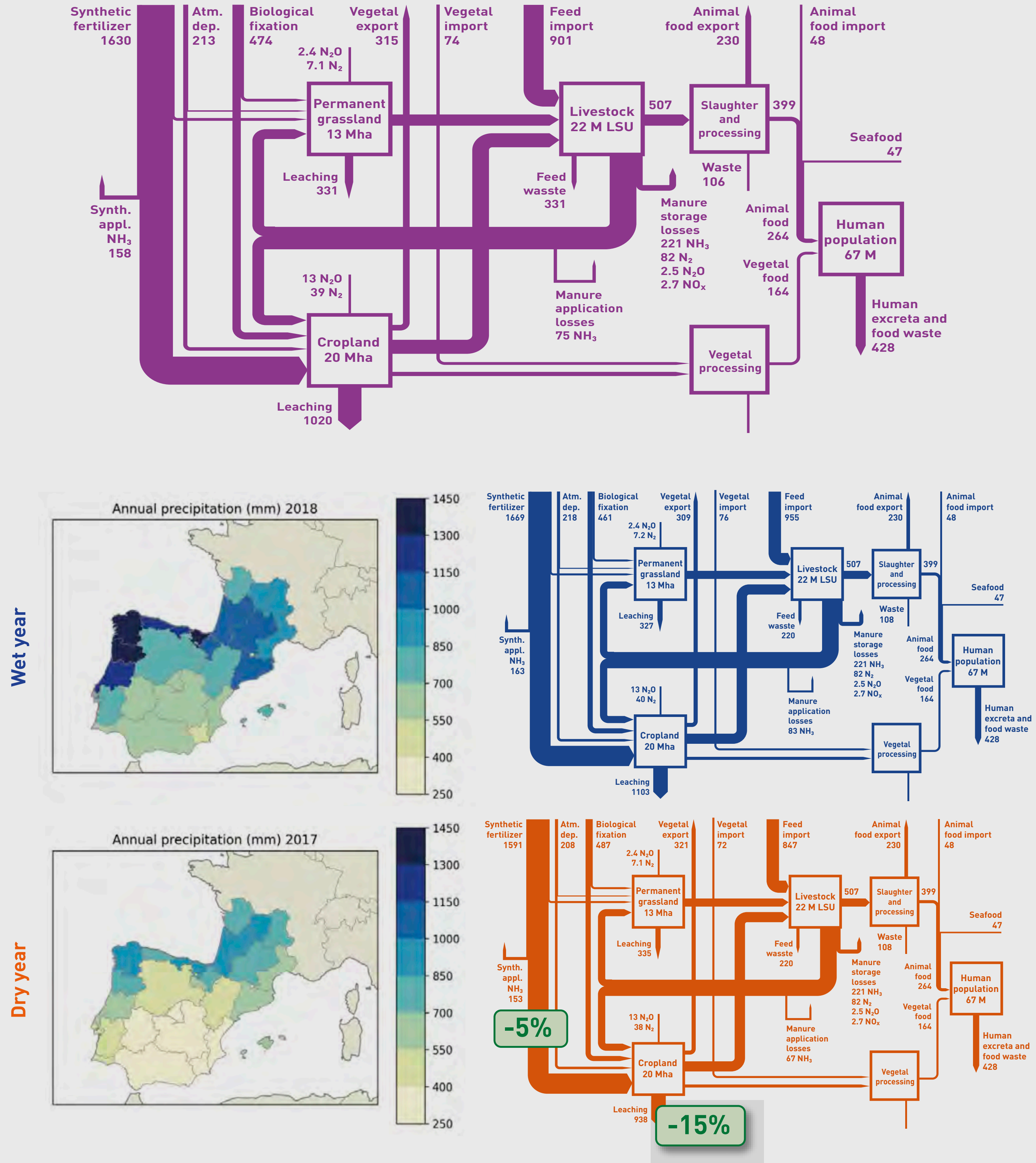

Figure 2.15 | Nitrogen dynamics for the entire SUDOE territory (southwestern Europe) shown through the GRAFS approach (Billen et al., 2014) with a distinction between wet and dry years. Interannual variations associated with the Mediterranean climate between dry and wet years could lead to reductions in synthetic N entering in the system (–5%) as well as N pollution in the form of nitrate leaching (–15%).
Source: AgroGreen–SUDOE project (https://agrogreensudoe.org/en/impact-visualizer/)

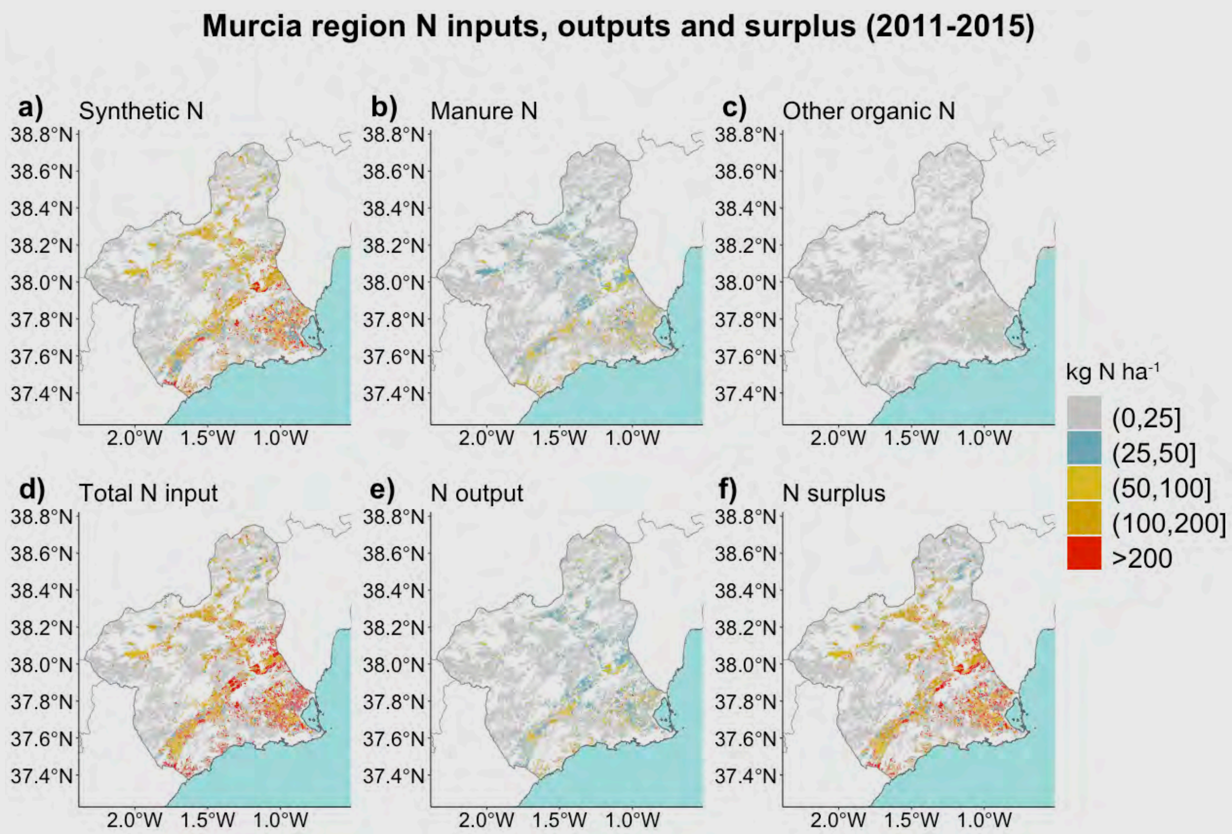

Figure 2.16 | N applied to agricultural soils in the Murcia region (kg N ha^{-1}): synthetic N (a), N in animal manure (b), N in other organic sources (c), total N input (d) and N output (e), and N surplus (f) (mean for 2011–2015).

Source: Sanz-Cobena et al. (2023).

2.4 The WEFE cascade from the energy change perspective

Energy is linked to all the nexus components through a variety of interactions (Sargentis et al., 2021). Regarding water, hydroelectric energy can only be generated if water is readily available in rivers or reservoirs, while the cultivation of plants for biofuel consumes significant amounts of water. Also, groundwater (the world's most extracted natural source) needs energy to be pumped; natural water, clean water, and wastewater need energy for treatment and transportation; and water distribution, and especially desalination, are energy-intensive processes. The extraction of fossil energy (conventional and unconventional) also requires water, as well as hydrogen. This is particularly crucial as the industry often operates in regions characterised by high temperatures and water scarcity. Regarding food, food production consumes 30% of total energy globally (harvesting, tillage, processing, storage) and the production of fertilisers is an energy-intensive process. On the other hand, there is competition between producing food grains for food, feed, or biofuel (e.g. corn, soya). And of course, through the consumption of food, energy is provided for our organs to function. Land is a central element that plays a key role in this context. The competitive relationship of land uses with the water–food–energy nexus is linked to ecosystems. Land is used for mining and extracting materials for energy production, cultivation of biofuel plants, creation of reservoirs in hydroelectric dams, ground-mounted photovoltaic (PV) panels and onshore wind turbines, creating competition with the cultivation of food. Biofuel plants use land and water to produce energy instead of food. Ground-based PV panels use land to produce energy without water. Using the land for reservoirs, hydroelectric projects produce energy using water (Sargentis et al., 2021). The related cascading effects mediated through the different drivers of change identified in *Section 2.4.1* need to consider all these interactions and identify potential synergies and trade-offs.

2.4.1 Impact of drivers of change on energy security

2.4.1.1 Climate change and climate policies

Energy production is the sector most responsible for climate change in the Mediterranean, accounting for 74% of total GHG emissions (Menichetti, 2021). This energy is later used by different sectors, like agriculture, building, industry, or transport. However, the energy sector is also impacted by climate change, with challenges to the stability and reliability of energy systems, both conventional and renewable (e.g. Solaun & Cerdá, 2019; WMO, 2022; Zapata et al., 2022). The main impact of climate change on energy is mediated through water scarcity (see *Section 2.2.3*). In Morocco, for the same installed capacity, the electricity produced in 2021 was about half the amount generated in 2011, and one third of the electricity generated in 2010. Yearly variations are significant and, despite some exceptions, depict a decreasing trend in electricity generation. The same can be observed for Tunisia (*Table 2.3*). The significant variations across the years are related to reduced rainfall, and to water management, which is prioritised as follows: (1) drinking water; (2) agricultural use; and (3) electricity generation.

Cumulative installed hydropower capacity in the Mediterranean stands at nearly 120 GW and represents 18% of total electricity capacity and 13% of electricity generation. If rainfall patterns drop drastically, energy availability in the region will be affected, with increasing energy security concerns. The decline in hydropower and thermoelectric power usable capacity is higher than global estimates (2.5–7.0% for hydropower in 2050 and 10–15% for thermoelectric power) (Drobinski et al., 2020a). Although solar photovoltaics and wind power are growing rapidly, thermoelectric power, together with hydropower, will most likely remain the dominant power-generating technologies throughout the twenty-first century (Drobinski et al., 2020a). In addition to hydropower electricity production, water stress is also an issue of concern for oil refineries and thermal power plants in the Mediterranean, most of which are located in highly water stressed areas (IEA, 2022). Moreover, nuclear power plants not only depend on water for cooling but are also often located in low-lying coastal areas and are therefore potentially vulnerable to sea level rise and weather-related flooding (*Figure 2.17*).

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Morocco												
Capacity (MW)	1770	1770	1770	1770	1770	1770	1770	1770	1770	1770	1770	1770
Generation (GWh)	3631	2139	1816	2990	2033	2282	1662	1565	1998	1654	1290	1213
Load factor (%)	23	14	12	19	13	15	11	10	13	11	8	8
Tunisia												
Capacity (MW)	62	62	62	62	62	62	62	62	62	62	62	62
Generation (GWh)	50	54	110	60	56	70	45	17	17	66	46	28
Load factor (%)	9	10	20	11	1à	13	8	3	3	12	8	5

Table 2.3 | Annual production from hydropower over the last 10 years as compared to installed capacity.
Source: elaborated from ONEE[7] and STEG statistics[8].

7 http://www.one.org.ma/

8 https://steg.com.tn/fr/

It is expected that climate change will lead to decreasing mean wind, wind energy potential and strong winds in North Africa and Mediterranean regions as a consequence of the poleward shift of the Hadley cell in the RCP4.5 and RCP8.5 scenarios by the middle of the century or beyond, and for a global warming level of 2°C or higher (Ranasinghe et al., 2021). However, this is not the case for the whole Mediterranean and for all seasons. For example, EURO-CORDEX regional climate simulations at the 12 km grid resolution over the twenty-first century indicate a significant increase of Etesian wind frequency and intensity in the summer over the Aegean Sea, under the two emission scenarios, RCP4.5 and RCP8.5, implying that future wind power potential in the Aegean Sea will be significantly increased by the end of the century (Dafka et al., 2018, 2019). Furthermore, extreme events can cause damage to production and distribution infrastructures with disruptions in supply, transportation and storage, and potential contamination of the natural environment (Brown et al., 2014; Patt et al., 2013).

Despite these risks, the number of strategy documents (National Adaptation Plans, Long-Term Strategy or Nationally Determined Contributions) submitted by Mediterranean governments to the United Nations Framework Convention on Climate Change (UNFCCC) and which mention energy as a climate adaptation sector, is fairly low. In southern Mediterranean countries, Morocco and Tunisia have developed Carbon Neutrality Strategies for 2050. Achieving the Paris Agreement commitment (UN, 2015) to hold the increase in global average

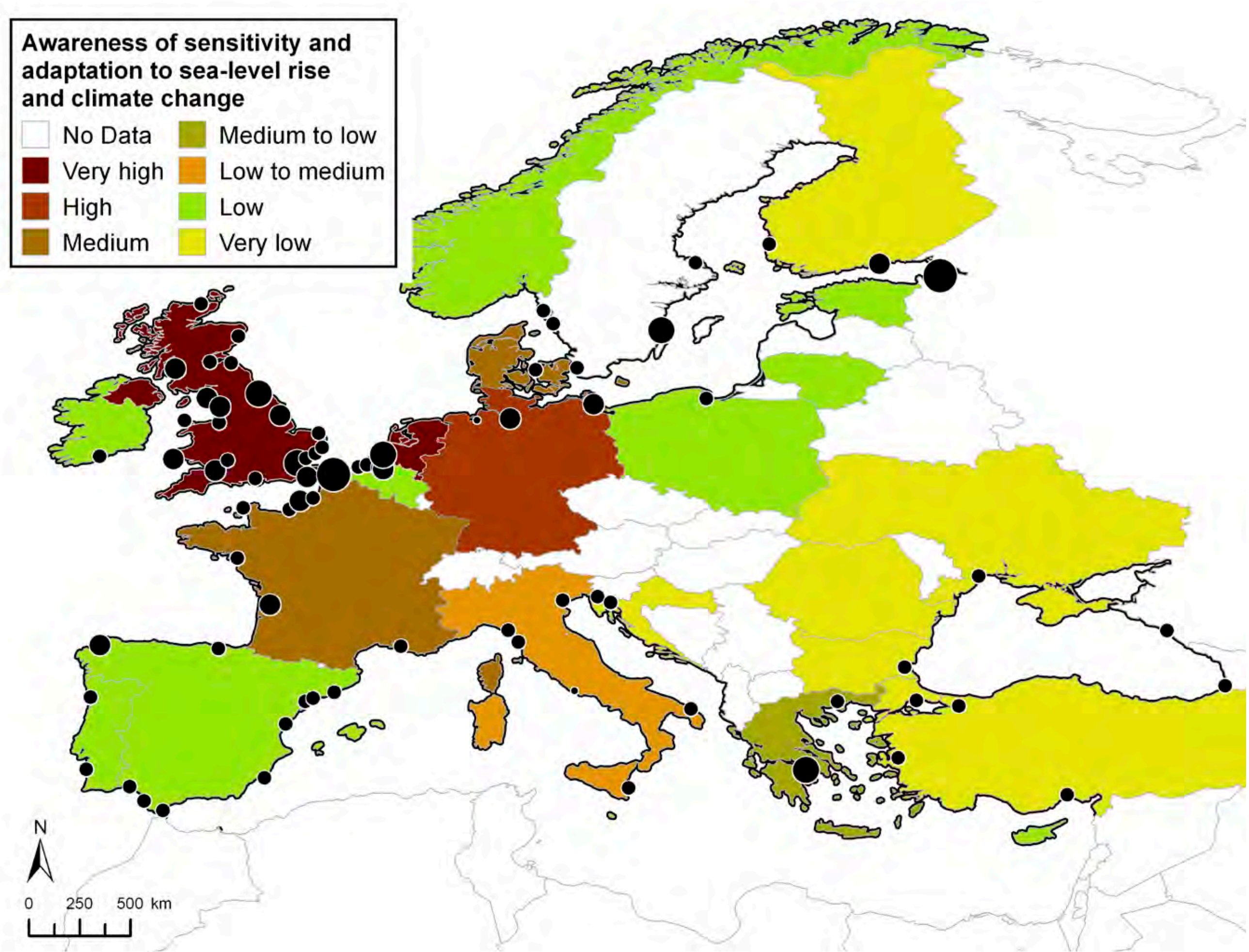

Figure 2.17 | Oil, gas, liquefied natural gas (LNG), tanker and nuclear terminals in Europe (where at least two facilities exist) with status of awareness of climate change and sea level rise.
Source: Brown et al. (2014).

temperature to well below 2°C above pre-industrial levels means reducing CO_2 emissions by approximately 50% between 2050 and 2100, alongside a reduction of emissions from other greenhouse gases linked to energy. Policies to reduce emissions associated with electricity production can be divided into three categories: carbon-intensity reduction, increase in energy efficiency, and reduction of consumption. For carbon-intensity reduction, cutting CO_2 emissions in half is equivalent to reducing the carbon content of energy by approximately 75% (Drobinski & Tantet, 2022). The Mediterranean is still a long way from decarbonising its energy system, and significant efforts are needed to accelerate the transition and meet climate mitigation goals. In practice, this means promoting renewables. Traditionally, the most exploited renewable energy sources have been biomass and hydropower. In terms of hydropower, dams all over the world produce a large amount of electricity, but a large part of the resource is already exploited (Grill et al., 2019), and they have considerable impact on ecosystems (Kuriqi et al., 2021). Biomass is heavily limited by the regeneration rate of forests, and can therefore hardly be considered carbon neutral (Sterman et al., 2018). Geothermal energy contributes in a few countries. In recent years, wind and solar solutions have entered the energy mix, for both electricity and heat production. Most southern Mediterranean countries lie in the so-called sunbelt, with global horizontal irradiance (GHI) values ranging from 1600 kWh m^{-2} yr^{-1} in coastal areas to 2600 kWh m^{-2} yr^{-1} in the desert, and direct normal irradiance (DNI) varying from 1800 kWh m^{-2} yr^{-1} to more than 2800 kWh m^{-2} yr^{-1}. They are therefore suitable for the development of both solar power (solar PV, concentrating solar) and solar heating and cooling technologies. Currently, the deployment status is far below the potential for both technologies (Resch et al., 2015). The potential is also very high for wind. While onshore wind has already reached a cumulative capacity of over 90 GW, the development of offshore capacity is rapidly accelerating and could lead to more than 20 GW and up to some 50 GW of additional capacity by 2035, according to national energy and climate plan objectives and market trends. In sum, despite quasi-stable oil-based energy production between 1995 and 2016, coal gradually decreased, primary energy production from natural gas doubled, while the contribution of nuclear energy and renewable energy sources increased by around 40%. However, promotion of renewables needs to take into consideration environmental protection and avoid conflicts with other land and sea uses through accurate maritime and land spatial planning, since this can have cascading impacts on other nexus components, particularly ecosystems and food (*Section 2.4.2*).

Finally, climate change impacts energy through changes in demand for heating and cooling buildings (temperature-sensitive energy demand). Overall, in continental areas, energy demand trends for heating and cooling were weak (under 10%) from 1941–1960 period to 1981–2000 period and increased (by more than 10%) from 1981–2000 period to 2021–2040 period. Increasing trends in cooling energy demand are more pronounced than decreasing trends in heating (Deroubaix et al., 2021). However, quantification of global warming impacts on future energy demand is still highly uncertain, despite being a key issue for accurate energy planning.

2.4.1.2 Population growth and lifestyle changes

Demographic trends and industrialisation (see *Section 2.1.1*) have a direct impact on energy systems. In a "Net Zero Carbon" scenario[9], energy demand in the South and East Mediterranean would increase by 2% in 2050 compared to current levels, as opposed to a 40% reduction in the North, as a consequence of contrasted demographic and economic trends (OME, 2022). In absolute values, this would translate into almost 19000 PJ in the South against some 15000 PJ in the North in 2050. Energy intensity would be higher in the South (1496 TJ k€$^{-1}$) than in the North (1373 TJ k€$^{-1}$) (OME, 2022), while per capita energy consumption would be higher in the North (76 MJ), than in the South (40 MJ), with a Mediterranean average of 51 MJ. These differences are linked to different lifestyles and currently, there are already high disparities between countries in per capita energy consumption. In 2022, according to OME

9 The « Net Zero carbon » or "ProMed" scenario has been developed by OME within the framework of its Mediterranean Energy Perspectives publication and with the co-funding of the European Commission. It assumes reaching carbon neutrality for the entire Mediterranean region to the 2050 horizon.

analysis (OME, 2023) per capita energy consumption was 108 MJ in the North Mediterranean (140 MJ in France, 53 MJ in Malta), against an average of 52 MJ in the South Mediterranean (25 MJ in Morocco, 18 MJ in Mauritania). Globally, 40% of current global energy use would be sufficient to provide universal decent living standards in 2050, while the energy consumption of a super-rich global 1% could equal that required to provide decent living standards (i.e. what is appropriate for sufficiency) for 1.7 billion people (Millward-Hopkins, 2022).

2.4.1.3 Urbanisation

Due to urbanisation trends, transportation systems are being redesigned to accommodate for a wider shift towards electric vehicles, biofuels, biomethane and other low-carbon technologies. In fact, the transport sector is currently, with power generation, one of the main players responsible for GHG emissions in the Mediterranean and is the sector with the highest growth in emissions in recent decades, especially in southern Mediterranean countries (UN DESA, 2022). It is also the sector with the highest energy intensity and the largest indirect contribution to primary energy imports – mainly oil, and associated energy dependence for non-producing countries. Under current trends, energy demand for the transport sector would increase by 35% and would still be heavily reliant on oil with an 84% oil share in 2050. To achieve carbon neutrality, the transport sector will need to be heavily decarbonised with oil dropping to about 8% of transport energy consumption by 2050. Sustainable transport (pedestrian and bicycle mobility) must also develop, and collective transport must be promoted.

Since the mid-1970s, waste management has become a major concern for Mediterranean countries. Waste represents an enormous loss of resources in the form of both materials and energy, and contributes about 5% of total GHG emissions. If not appropriately managed, waste can create a number of direct and indirect risks to both humans and the environment. Although significant effort has been invested by several Mediterranean countries, 58% of collected waste is disposed of in open dumps and 31% in sanitary landfills, while less than 10% of collected waste is recycled or composted (EEA & UNEP/MAP, 2014). Integrated waste management policies based on regional and international best practices can help rapidly improve the situation and turn a serious environmental issue into an opportunity for resource reuse and generation of sustainable energy.

The rapid urbanisation that occurred in Mediterranean countries also creates another impact in terms of energy consumption from buildings, accounting for 38% of energy consumption in the region (Plan Bleu, 2012). Despite the expected increase in demand for cooling services, due to rising average temperatures, as well as for other electrical uses, the building sector represents important potential for energy savings, integration of renewable energy technologies and emissions reduction.

2.4.1.4 Industrialisation and pollution

The industrial sector is the second largest energy-consuming sector in the Mediterranean after transportation, accounting for 28% of total final consumption in 2020. Under current trends, energy consumption in the industry is expected to increase by 60% in 2050, while the share of renewable energy technologies is set to grow by only 15% (OME database). Energy efficiency measures can curtail the increase in demand.

The case of Egypt highlights some of the most critical issues related to growing industrialisation, that hold true in other Mediterranean countries (EEA & UNEP/MAP, 2014). In the last decade, industry has developed rapidly in Egypt, and is expected to keep growing at a rate of about 7% per year. The continuous growth of industrial production has led to both human health and environmental stresses. About 60% of all CO_2 emissions, and 10% of SO_2 emissions originate from industry. Based on the 3rd Nationally Determined Contribution (NDC), estimated CO_2 emissions from industry were 23.4% for 2005/2006. The main source categories for CO_2 emissions respectively are cement, ammonia not used in the urea, iron and steel industry, and lime production (EEAA, 2016). To tackle this problem, an objective of decreasing the pollution loads generated by industries by at least 50% has been set.

2.4.1.5 War

The relationship of energy with conflicts has been described in three ways: (1) The energy system as an objective in conflict (linked to energy security, control system structures and competition for resources); (2) The energy system as a means in a conflict (linked to deliberate reduction of flow by supplier or user and disturbance induced by a third party); and (3) The energy system as a cause of conflict (linked to the resource curse/local abundance in a country, environmental degradation, reduced security of supply or interactions with food prices) (Månsson, 2014). When energy production and distribution infrastructure are damaged, it creates not only problems for energy access but also for the environment.

The 2010 Arab spring led to more serious conflicts in Libya and Syria, which are still heavily affecting their social, economic, and energy systems. When the social upheaval started in Libya in early 2011, the country was the largest oil producer in the Mediterranean. Annual production dropped from 90 to 26 Mtoe between 2010 and 2011, and after slightly recovering, it dived again as a consequence of the nationwide blockade (OME, 2022). There is a similar story with gas production. Syria's relatively modest oil production was already on the slide when war broke out in the country. Sanctions in December 2011 halted the operations of international companies. Most large oil fields and infrastructure are damaged or non-operational.

Besides the clear impact of war on fossil fuel production and trade, the current instability holds back the spread of energy efficiency and renewable energy projects. For example, the 60 MW Derna onshore wind farm in Libya announced in the early 2010s is still shelved. Of course, such a situation not only directly impacts the countries concerned, but indirectly affects the development of regional projects, thus slowing down the energy transition process in the region.

An additional point involves the increasing role of fossil energy supply in the Euro-Mediterranean dialogue. After the approval of REPower EU, Algeria has become the third biggest supplier of gas to the EU. Similarly, a Memorandum of Understanding between the EU, Israel and Egypt was signed in June 2023 to increase exports of natural gas to Europe from these two countries (Directorate-General for Energy, 2022). These agreements must not undermine the need to foster energy transition and sustainable development under a nexus approach.

2.4.2 Cascading impacts of climate-induced energy changes on water, food and ecosystems

The main impacts of climate change on energy are mediated through water scarcity, impacts on infrastructure or changes in demand, as well as the mitigation policies to which all countries are committed and that imply changing the energy production mix to increase the proportion from renewable resources (*Section 2.4.1*). However, introducing a nexus perspective shows that the development of renewable energies as low-carbon solutions is not as easy. Two major challenges affect the WEFE components in a low-carbon transition. First, the fluctuating nature of the capacity factor, which measures how often an energy production plant is running at rated power. In the Mediterranean region, the capacity factor of onshore wind energy sources ranges between around 20% in Italy and France to 25% in Spain up to nearly 30% for Portugal and Türkiye (Gönül et al., 2021), reaching 45% in Morocco (Bouramdane et al., 2020, 2021). Capacity factors of offshore wind energy resources can reach up to 50% in the region (Kalogeri et al., 2017; Nøland et al., 2022). For solar PV, the capacity factor drops to around 20% on both shores of the Mediterranean Sea (Bouramdane et al., 2020, 2021) while for concentrated solar power (CSP), it can reach 35% in Morocco (Bouramdane et al., 2020, 2021). Capacity factors of renewable energy sources in the Mediterranean are 3 to 4 times smaller than operational thermal power plants (which can reach 90%) (IEA, 2020). Therefore, for a given energy production, the installed capacities of wind or solar energies are 3 to 4 times higher than for conventional thermal production. Also, the space required per kWh is several orders of magnitude larger compared to conventional electricity production methods (van Zalk & Behrens, 2018), which is a problem, because land use change is one of the main causes of biodiversity loss (IPBES, 2019). According to Nøland et al. (2022), power densities of conventional thermal energy plants differ by a factor of between 50 and 500 (nuclear around 500 W m^{-2}, natural gas around 350 W m^{-2} versus around 1-10 W m^{-2} for wind, PV and biomass). Assuming that all areas are amenable to each source and that they face no limitations in terms of scalability other than their mean annual energy densities, the spatial requirements for the different power sources to meet 100% of the 2020 primary energy use for Europe, the

Middle East and Africa are shown in *Table 2.4* (Nøland et al., 2022). This shows that for renewable energy sources, the spatial requirements already necessary in the Mediterranean region to fulfill 100% of the primary energy use ranges typically between 1% for hydro or solar PV to about 10% for onshore wind in Europe and the Middle East and between 0.1% for solar PV to about 2% for onshore wind in Africa. For biomass, the spatial requirements already exceed 100% of Europe and the Middle East. By comparison, the spatial requirements for nuclear or natural gas never exceed 0.7%. With energy demand in MENA countries expected to double by 2040 from 2015 (Drobinski et al., 2020b, 2020a), the proportion of land dedicated to energy production could reach more than 10% of total land with potential consequences on land degradation or biodiversity loss.

In addition, the impact of energy on land occupation in transitioning to renewable energy can conflict with food production (Sargentis et al., 2021) (*Figure 2.18*). The growing availability of arable land in Mediterranean regions, as a consequence of the decline of cereal cropping systems and grain legumes, provides ample opportunities for performing successful feedstock production in unmanaged areas (Pulighe et al., 2019). Also, integrated approaches in which energy crops are introduced into the rotation cropping system for local use can reduce burdens on land (ranging from −32 to −8%) and improve environmental farming sustainability (Solinas et al., 2015). In Greece, the impact of diverting food crops to produce bioenergy shows strengths including the creation of direct and indirect jobs (biofuel production industry), diversity of energy supply, and a positive contribution to the greenhouse effect. Weaknesses include environmental impact, and dependence on land availability (additional need for arable land other than that required to grow food) (Paschalidou et al., 2016). Energy communities and multifunctional land use have proven to improve implementation possibilities and consensus at local level (Abouaiana & Battisti, 2022). Offshore wind energy production also requires careful consideration, as it can impact the marine environment through noise

	REGION		
POWER SOURCE	EUROPE (%)	MIDDLE-EAST (%)	AFRICA (%)
Nuclear	0.031	0.021	0.002
Natural gas	0.064	0.043	0.005
Hydropower	0.712	0.958	0.455
Solar (CSP)	1.181	0.787	0.093
Solar (PV)	2.422	1.615	0.192
Wave	3.023	2.015	0.239
Geothermal	4.918	3.279	0.389
Solar (rooftop)	6.486	2.508	0.110
Wind (offshore)	6.170	4.113	0.488
Tidal	8.451	5.634	0.669
Wind (onshore)	6.154	7.547	1.845
Biomass	184.615	123.077	14.615

Table 2.4 | Spatial requirements for the different power sources to meet 100% of primary energy use, normalised by land area.
Source: Nøland et al. (2022).

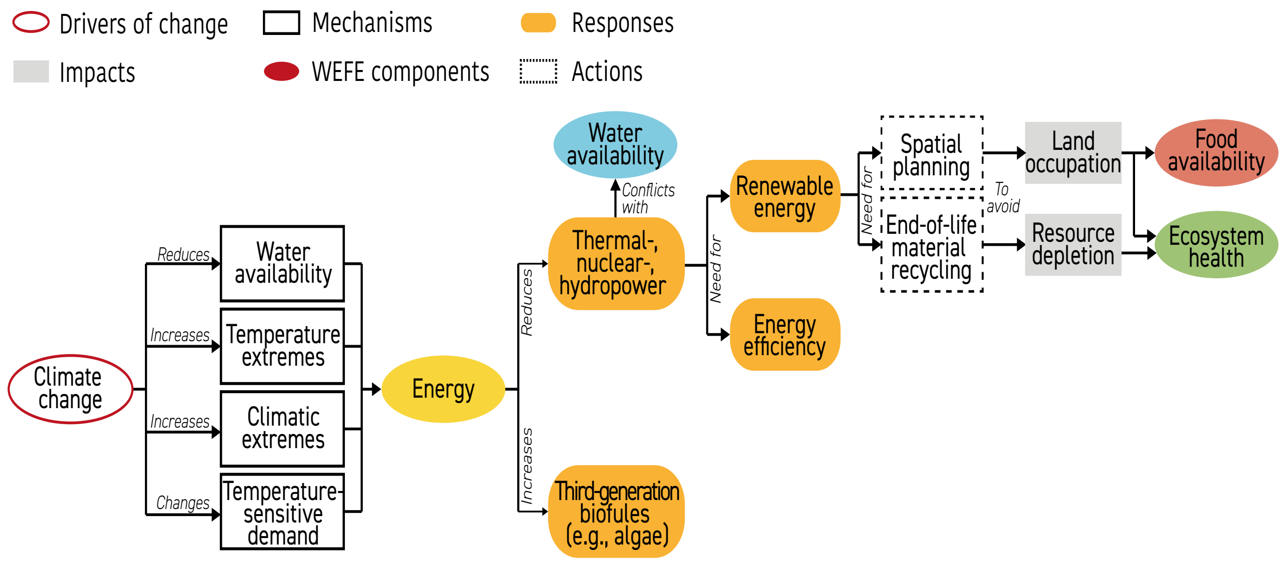

Figure 2.18 | Example of cascading impacts of climate-induced energy changes on water, food, and ecosystems.

emissions that affect marine wildlife. The Convention on the Conservation of Migratory Species of Wild Animals has published Best Available Technology (BAT) and Best Environmental Practice (BEP) for mitigating noise from this technology (Weilgart, 2023).

Finally, increasing energy production implies more water. In Europe, water withdrawals for energy are similar to those for agricultural irrigation. A small fraction is eventually consumed (6% for EU countries, nevertheless with large disparities between countries), and the remainder is returned to the hydrological system (Adamovic et al., 2019). In the MENA region, the share dedicated to irrigation is much higher (80%) (World Bank, 2018), as the climate is much more arid. But the energy sector still represents a significant proportion of withdrawals which could evolve over time due to improved technologies associated with the water-energy nexus.

In sum, accurate spatial planning is needed to avoid adverse effects such as loss of biodiversity and conflicts between different land and sea uses. If priority is given to system integration of renewable energies (building-integrated, industrial areas, non-arable land, mixed-cropping systems, etc.), potential conflicts between energy and non-energy use of soil can be avoided. This point is really crucial as the added value of renewable energies is their flexibility and modularity compared to conventional technologies. It is important for policymakers to adopt clear rules and regulations to prevent the deployment of renewable energy following the same pattern as conventional energies. Calls for tenders for renewables should, for example include the land occupation aspect, and in general more of a nexus approach to minimise conflicts with water, food and ecosystems. Reducing energy demand is also crucial considering the biophysical limitations for production.

2.5 The WEFE cascade from the ecosystems change perspective

2.5.1 Impact of drivers of change on ecosystem health and services

2.5.1.1 Climate change

The Mediterranean Basin is undergoing several climatic alterations that are transforming this previously biodiversity-rich region (Moatti & Thiébault, 2018). Rising temperatures, changes in rain patterns, more frequent and stronger extreme weather events (such as wildfires, storms, and droughts) and rising sea levels, can worsen the condition of sensitive Mediterranean ecosystem species, disturbing the already delicate balance (Cramer et al., 2018; Lange, 2020; Seneviratne et al., 2021). These changes can be seen through increased vulnerability of endemic and keystone species, shifts in vegetation, migration of fauna, phenological changes and ecological asynchrony, as well as the expansion of arid and semi-arid zones, among others.

Vulnerability of endemic and keystone species

Endemic species, uniquely adapted to the Mediterranean climate, face increased vulnerability. The restricted geographical ranges of these species leave them with limited options for migration or adaptation, rendering them susceptible to temperature-induced stress. This poses a considerable threat to the rich biodiversity that characterises Mediterranean terrestrial ecosystems (Médail, 2017). For instance, warmer temperatures can impact the Iberian lynx (*Lynx pardinus*), endemic to the Iberian Peninsula, by changing the lynx's preferred habitats and the abundance of its primary prey, the European rabbit (*Oryctolagus cuniculus*) (Fordham et al., 2013; van Hassel & Bovenkerk, 2023). The Atlas cedar (*Cedrus atlantica*), an endemic tree species in the Atlas Mountains of North Africa, faces increased vulnerability due to temperature-induced stress, especially as warmer conditions impact its distribution and growth. Elevated temperatures and altered precipitation patterns also have the potential to augment the proliferation of pests and diseases affecting this tree (Cheddadi et al., 2017). As trees are weakened by unfavourable environmental conditions, an increasingly large proportion is expected to become susceptible to pathogens. This has twofold implications: (1) many trees will die, reducing the standing biomass; and (2) the pathogen population will build up to the point of threatening trees that could, perhaps, resist a light attack but not a heavy infestation. Losses will probably be greatest for trees on the edges of their natural distribution, where a small change will make the environment unsuitable for them. Some forest diseases now considered minor may become serious (Resco de Dios et al., 2007).

Keystone species play pivotal roles in maintaining ecosystem structure and function. Whether they are dominant plant species shaping landscapes or top predators regulating populations, these keystone species are sensitive to changing climate conditions. Their decline or altered behaviour can trigger cascading effects throughout the ecosystem. holm oak (*Quercus ilex*), a dominant tree species in Mediterranean forests, plays a key role in shaping the structure and composition of these ecosystems. It provides habitat, influences nutrient cycling, and regulates water availability. However, changes in precipitation patterns and increased frequency of droughts associated with climate change pose threats to the health of Holm oak forests (Puig-Gironès et al., 2023). Reduced water availability can affect the distribution of this keystone species and impact the diverse flora and fauna dependent on these ecosystems, especially in less favoured microclimates (Principe et al., 2019). The pine processionary moth (*Thaumetopea pityocampa*) is a keystone species in Mediterranean pine forests, influencing vegetation dynamics and nutrient cycling. It also serves as a food source for numerous bird species. Warmer temperatures and altered precipitation patterns can affect the life cycle and population dynamics of the pine processionary moth. This, in turn, can impact the entire trophic cascade within the forest ecosystem, affecting both flora and fauna (Hódar et al., 2003).

Shifts in vegetation and migration of fauna

Rising temperatures are inducing significant shifts in the composition of plant and animal species within terrestrial ecosystems. As thermal conditions become less suitable for certain species, there is an observable migration of vegetation zones to higher altitudes, altering the dynamics of ecosystems traditionally characterised by distinct plant communities. Heat-tolerant and drought-resistant species may become more dominant, leading to changes in the composition of plant communities. This phenomenon poses a threat to endemic and specialised species adapted to cooler temperature ranges, leading to potential biodiversity loss, and impacting the overall biodiversity and structure of Mediterranean ecosystems (Peñuelas et al., 2017). In addition, if temperatures change as rapidly as predicted, then the reassembly of ecological communities will need to take place within the lifespan of individual trees. As communities are the result of interactions between organisms as well as between organisms and their abiotic environment, rapid climate change may be expected to alter species assemblage composition (Resco de Dios et al., 2007). Changing precipitation patterns, including altered rainfall amounts and distribution, influence the structure of terrestrial ecosystems. Wetland and forest ecosystems may experience changes in plant composition and distribution as species adapt to new moisture regimes. Species adapted to specific precipitation patterns may face challenges as their habitats change, potentially resulting in declines for certain plant species and impacting associated fauna (Erol & Randhir, 2012).

Examples of shifts in vegetation due to alterations in temperature and moisture regimes include Morocco's

Atlas Mountains. They are currently warming and, consequently, alpine flora, including rare cold-loving species, are moving upwards. Alpine vegetation displacement compresses the habitat for high-altitude plant species, in turn, affecting the organisms that depend on this vegetation for food and shelter (Cheddadi et al., 2017). This upward shift in alpine plant species is also observed in the Sierra Nevada mountain range. Some species that were normally limited to certain heights, or dependent on particular moisture regimes are now found at higher levels (Winkler et al., 2019). Endemic and specialised plant species suitable for cooler temperatures and certain moisture regimes are facing a reduction in habitat availability, which increases the likelihood of local extinction and biodiversity loss (Benito et al., 2011). Changing climatic conditions in the Peloponnese in Greece are affecting the distribution of forested areas. The mix of deciduous and evergreen species is being displaced as traditional forest boundaries move to higher elevations. Vegetation migration leads to a reshuffling of dominant tree species that changes the overall visual landscape and habitat suitability for associated fauna (Koulelis et al., 2023). Southern Spain experiences longer hotter days with lower precipitation. *Cistus* and lavender Mediterranean shrublands are now changing as a result of these changing conditions. These heat-tolerant shrub species are growing at the expense of drought-intolerant plants, altering the biodiversity and ecological dynamics of these landscapes. This kind of shift may further affect herbivores and pollinators, which depend on certain plant species (Gallego Fernández et al., 2004). In the Camargue wetlands in France, changes in rainfall patterns, which contribute to fluctuations in water levels, impact the composition and distribution of wetland plant species, including some critical species for waterfowl birds. It can alter the availability of good nesting and foraging grounds for birds (Nager et al., 2010).

Rising temperatures are also inducing shifts in distribution of animal species (Aurelle et al., 2022; Stefanescu et al., 2003). Birds, insects, and small mammals may migrate to higher temperatures (Maiorano et al., 2011). This may result in shifting predator-prey relations, resource competition, and modifications in species interactions in mountainous and hilly regions. Butterfly distribution in the Sierra Nevada mountain range has been affected by increasing temperatures. They are migrating to higher latitudes where climatic conditions better suit their life cycle requirements. The distribution of butterflies may also alter their interactions with plants, such as pollination dynamics. Moreover, it may adversely impact other butterfly-dependent species like insectivorous birds (Nice et al., 2014). Changing hotter temperatures in the Atlas Mountains are also changing the distribution of ant species. Ant colonies can migrate to higher elevations due to unfavourable temperatures, and the search for appropriate nesting grounds. This can have cascading effects on ecosystems, affecting seed dispersal, soil nutrient cycling etc. and other invertebrates (Ziyadi et al., 2019). There is also evidence of the migration of lizards and snakes in Crete, to areas with higher elevations. Changes in the distribution of reptiles can alter local ecosystems, including predators and prey (Karameta et al., 2023). In the Pyrenees mountain range, bird species, particularly those adapted to cooler conditions, are migrating to higher elevations where temperatures remain within their preferred range. These changes in the distribution of bird species can lead to altered predator-prey dynamics, competition for nesting sites, and shifts in the availability of food resources in mountainous regions (García-González et al., 2016).

Phenological changes and ecological asynchrony

The warming climate is disrupting the timing of key ecological events, known as phenology, affecting the synchrony between species interactions. Changes in the timing of phenological events, e.g. flowering and migration, can lead to mismatches between mutually dependent species, such as pollinators and flowering plants or predators and prey. This ecological asynchrony can have cascading effects on the entire ecosystem, from plants and pollinators to herbivores and predators. The spatial variability of flowering dates is also reduced during warm and dry years, especially for spring events (Gordo & Sanz, 2010). This reduction in spatial variability can also affect dependent species.

Ecological asynchrony due to changing climate patterns might occur when the timing of plant flowering shifts, affecting the availability of nectar and pollen for pollinators. If pollinators, such as bees, do not adjust their life cycles accordingly, a phenological mismatch can occur, potentially leading to reduced pollination success and seed production (Morton & Rafferty, 2017). Almond trees (*Prunus dulcis*) in Spain typically rely on honeybees for pollination. With warmer winters, almond trees are flowering earlier. However, honeybee activity might not adjust accordingly, leading to a potential phenological mismatch. If bees are not present when the almond trees are in full bloom, it can result in reduced pollination and almond yields (Henselek et al., 2018). On the other hand, climate change is influencing the timing of seasonal events, such as the arrival of migratory birds in the Iberian Peninsula (Gordo & Sanz, 2006). The altered timing of bird migration may no longer align with the peak availability of their insect prey. If migratory birds arrive before or after the peak abundance of their prey species, this can disrupt food availability, affecting the reproductive success of birds and potentially impacting insect populations (Acácio et al., 2022).

Genetic, epigenetic and metabolic impacts

Climate change is causing rapid genetic, epigenetic, and metabolomic changes in Mediterranean plant species. Field studies of altitudinal gradients in the Montseny Mountains (Jump et al., 2006a, 2006b) and field-warming and drought-manipulation experiments in typical Mediterranean shrubland (Jump et al., 2008) have demonstrated rapid responses for the acclimation and adaptation (evolution) of species to climate change by taking advantage of the existing genetic variability in natural populations (Peñuelas et al., 2018). Alterations in gene expression not attributable to variations in DNA sequences have also been detected in holm oak (*Quercus ilex*) subjected to experimentally induced drought (Rico et al., 2014). In response to drought stress, Mediterranean shrubs and trees often increase the production of secondary metabolites such as phenolic compounds and flavonoids. These compounds play a role in antioxidant defence and protection against oxidative stress induced by drought. These compounds can have various functions, including antioxidant activity and defence against herbivores and pathogens (Rivas-Ubach et al., 2012, 2014, 2016). Changes in plant genetics, epigenetics and metabolomics have resulted in changes in morphology, physiology, growth, reproduction, and mortality, with some species more affected than others. These changes could lead to a future dominance replacement of trees by tall shrubs (Peñuelas et al., 2018).

Expansion of arid and semi-arid zones

Warming temperatures, changes in precipitation patterns and increased evaporation contribute to the expansion of arid and semi-arid zones in the Mediterranean, leading to desertification and habitat loss. Mediterranean ecosystems, generally dominated by sclerophyllous woody plants with a herbaceous or shrubby understory, have an array of physiological and morphological adaptations to cope with drought and nutrient scarcity (Gulías et al., 2002; Padilla & Pugnaire, 2007; Vilagrosa et al., 2010). Nevertheless, in coming decades, the projected level of drought and aridity may have important effects on the functioning and structure of Mediterranean plants, forests and shrublands (Peñuelas et al., 2018). Species adapted to more arid environments, such as succulent plants, may thrive, while others dependent on historically more temperate conditions and moisture regimes may face challenges (Maestre et al., 2012; Vallejo et al., 2005), including local extinctions (Prigent et al., 2018). In Catalonia (northeastern Spain), rising temperatures, new patterns of precipitation and other climatic changes are affecting ecosystems (Peñuelas et al., 2018). In Almería (southeastern Spain), intensive agriculture, coupled with increasing temperatures and altered rainfall, has contributed to soil degradation and desertification, leading to a decline in natural vegetation.

Altered precipitation patterns, including increased drought frequency, pose significant challenges to water-dependent ecosystems. Wetlands, riparian zones, and freshwater habitats are particularly vulnerable, affecting species dependent on these unique environments. For example, Doñana National Park is a UNESCO World Heritage Site known for its wetlands and biodiversity. Altered precipitation patterns and increased drought frequency, together with high intensity levels of underground water extraction for irrigation, have led to reduced water availability in the park's wetlands, resulting in habitat loss and changes in the composition of aquatic plant species. Species like waterfowl birds, amphibians, and migratory birds that depend on these wetlands for breeding and feeding also face challenges due to reduced water resources (García de Jalón et al., 2014; Green et al., 2017).

Changes in nutrient cycling

Reduced soil moisture may impact the nutrient cycle due to its effects on microbial activity, mineralisation and other processes. Additionally, changes in temperature and precipitation patterns can influence the timing and nature of biotic interactions, such as plant-microbe relationships, impacting nutrient cycling processes. Take, for instance, mycorrhizal associations between plants and fungi. Fungi play a vital role in natural ecosystems and strongly influence the dynamics of forest ecosystems, including the ability of trees to access limited nutrients and store carbon. Fungal productivity has already decreased in certain areas due to climate change (Morera et al., 2022). Projections estimate that most significant changes in total productivity, including mycorrhizal fungi, will occur in subalpine and montane pine forests. In contrast, saprotrophic fungi could potentially benefit from more significant changes in climate and boost their productivity in supra– and meso– Mediterranean regions at mid–range elevations (Morera et al., 2022). These changes in nutrient cycling suggest potential net losses in the capacity of Mediterranean forests and shrublands to act as carbon sinks (Peñuelas et al., 2018) and to provide other ecosystem services, such as soil conservation, water storing capacity, biodiversity, timber, mushroom and food production, tourism, and recreation (*Table 2.5*; Peñuelas et al., 2017).

Elevated sea levels may influence nutrient dynamics in land and water systems at the coast. Saltwater intrusion can lead to changes in nutrient availability in coastal ecosystems which affect the quality of soils and waters. In return, it may influence plant and microbial communities (Bellafiore et al., 2021). Additionally, ocean acidification and changes in the marine ecosystem due to increased CO_2 levels in the atmosphere may have consequences for nutrient cycling processes in the Mediterranean Sea (Hassoun et al., 2022).

Impact of extreme events on ecosystems

Extreme events, such as heatwaves, wildfires, intense storms, and heavy rainfall, can have profound impacts on the structure and function of ecosystems in the Mediterranean Basin (Hochman et al., 2022). Wildfires are a significant threat that can lead to the destruction of vegetation, including forests, shrublands, and grasslands. Loss of vegetation alters the physical structure of ecosystems, leading to habitat fragmentation, soil erosion and changes in species composition. Post–fire, ecosystems often experience shifts in plant and animal populations (Caon et al., 2014; Duguy et al., 2013). Heatwaves can cause extreme temperatures beyond the norm, stressing plant and animal species and disrupting normal ecosystem functions. They can also lead to increased evaporation, affecting water–dependent ecosystems (El–Madany et al., 2020). On the other hand, extreme temperatures in the Mediterranean Sea can lead to marine heatwaves, causing coral bleaching, changes in fish distribution, and altered plankton dynamics. These events can disrupt marine food webs and alter the abundance and distribution of marine species. Some extreme situations of mass mortality in the Mediterranean Sea have been reported (Garrabou et al., 2022). Finally, intense rainfall events leading to flooding, particularly in coastal areas and riverine ecosystems, result in soil erosion, loss of vegetation, and habitat degradation. This may also lead to the displacement of species adapted to specific moisture conditions (Terrado et al., 2014).

Changes in aquatic ecosystems

The Mediterranean Sea represents the highest proportion of threatened marine habitats in Europe (32%), with 21% listed as vulnerable and 11% as endangered, and seagrass ecosystems experiencing the most rapid decline (UNEP/MAP & Plan Bleu, 2020). Marine ecosystems in the Mediterranean are sensitive to sea surface temperature increases. This has resulted in the occurrence of coral bleaching events, changes in the distribution of fish species, and altered abundance of marine organisms (Calvo et al., 2011). Elevated sea temperatures have the potential to perturb the distribution and behaviour of marine species, thereby causing alterations in migration patterns and posing a risk to those that are most susceptible (Hoegh–Guldberg et al., 2014; IPCC, 2022; Nurse et al., 2014; Pörtner et al., 2014; Wong et al., 2014). Changes in fish distribution can have implications for local fisheries, altering catch compositions and potentially leading to shifts in predator–prey dynamics within the marine food web (Giani et al., 2012). Besides corals, marine heatwaves will likely cause increasing mass mortality events of benthic species, mostly invertebrate organisms, such as sponges, bivalves, ascidians, and bryozoans, and increase the risks of abrupt collapse of endemic species (Garrabou et al., 2019, 2021; Kersting et al., 2013; Rivetti et al., 2014, 2017). Increased carbon dioxide absorption, which contributes to ocean acidification, can be detrimental to marine organisms possessing calcium–carbonate shells or skeletons, including corals and molluscs. Phytoplankton net primary productivity is set to drop on average by 10% at the end of the century and up to 50% in some regions, such as the Aegean Sea, as a result of both nutrient limitation and vertical stratification, with possible negative impacts on marine food webs and ecosystems. Benedetti et al. (2018) estimated that the diversity of copepods is expected to decline across most regions of the Mediterranean, influenced by various factors associated with environmental changes, such as variations in temperature, ocean currents, and nutrient availability. Changes in the abundance and composition of copepod communities may lead to shifts in fish distribution, growth rates, and overall ecosystem dynamics.

The loss of corals has a significant impact on the marine life that relies on them for shelter and food (Antoniadou et al., 2023) and also affects the coastline by reducing natural protection against waves and storm surges (Baker et al., 2008). Rising sea temperatures, increased nutrient runoff, and changes in storm patterns can all lead to the decline of Posidonia oceanica meadows, a keystone seagrass species. This decline can have a significant impact on coastal ecosystems, affecting fish nurseries, nutrient cycling, and sediment stability, with cascading effects on other marine organisms (Pergent-Martini et al., 2021). Fluctuations in precipitation and changes in hydrological regimes also influence aquatic ecosystems. The alteration of river flows can alter fish migration, spawning, and the availability of suitable habitats. Freshwater and estuarine species face the challenge of adapting to changing salinity levels, impacting the composition and distribution of these communities (Cid et al., 2017; Erol & Randhir, 2012). Altered precipitation patterns, coupled with increased drought frequency, have contributed to the reduction of water availability in the Camargue wetlands. Drought stress has led to the loss of wetland habitats, affecting water-dependent species such as amphibians, waterfowl, and various aquatic organisms. Amphibians, in particular, may face decline due to the reduced availability of suitable breeding habitats (Fraixedas et al., 2019). These examples underscore the complex and interconnected nature of aquatic ecosystems in the Mediterranean Basin, where changes in sea surface temperatures and levels of precipitation have far-reaching consequences on coral reefs, seagrass meadows, fish populations, and overall biodiversity.

Impacts in island ecosystems

Mediterranean islands are hotspots for global biodiversity and lie in one of the areas of the world that is the most susceptible to climate change. These include phenological changes and upward elevation shifts of species and plant communities; although evidence is frequently contrasting for different taxa (Vogiatzakis et al., 2016). Threats are also evident, mainly for endemic species from most taxonomic groups, while communities in mountain and coastal regions are likely to be affected most. Furthermore, the limited space on islands (especially habitat availability and climatic range limitations) places a barrier on species range expansion (Vogiatzakis et al., 2016).

2.5.1.2 Land Use and Land Cover Changes (LULCC)

Sustainable land management and conservation of terrestrial ecosystems are crucial for achieving the SDGs. LULCC may arise from a range of situations that are not always negative for ecosystems: the disturbance of a native or semi-natural ecosystem; altering the management or purpose of already humanised systems (e.g. agroecosystems, urban systems); rewilding of ecosystems or restoration in its various forms – ecological, mitigation, remediation, rehabilitation, revegetation, etc. (Gann et al., 2019). Demographic and lifestyle changes have increased the pressure on Mediterranean ecosystems. There is a pressure to expand agricultural and urban areas, together with all the infrastructure necessary for their functioning, at the cost of occupying former natural areas, thus fragmenting, and reducing the size of natural ecosystems as well as the services they provide (Haddad et al., 2015; Salvati et al., 2016). On the other hand, land abandonment of former agricultural areas, now subject to lack of management, favour colonisation by invasive species (IPBES, 2023) and create conditions for uncontrollable fires (e.g. Delgado-Artés et al., 2022; Mantero et al., 2020). The abandonment of traditional agriculture in the Mediterranean has also contributed to reducing the endemic biodiversity of the ecosystem and its functional resilience (IPBES, 2023). Traditional Mediterranean agriculture had the benefit of being diverse (in space and time – e.g. rotations, seasonal products) and practiced on small areas, facilitating interactions with nearby natural ecosystems. Large scale monocultures, without the implementation of natural corridors or "stepping-stones" (areas of heterogeneity) for natural biodiversity to be able to transit between more natural ecosystems and multiply their genetic pool, have a strong negative impact on ecosystems' health. Over the past few decades, the Mediterranean region has experienced a rise in agricultural intensification, an expansion of cultivated land and a shift towards high-yield crops to satisfy increasing demand for food globally. Within this particular context, extensive regions of forests, grasslands, and other natural ecosystems have undergone a transformation process, converting them into agricultural fields. The aforementioned practices were found to be associated with substantial LULCC patterns in the Mediterranean region, resulting in detrimental effects on the well-being of ecosystems. The Mediterranean Basin emerges as a significant non-point source of nitrogen, predominantly from agricultural intensification (UNEP/MAP & MED POL, 2011). While moderate amounts of nitrogen, particularly in the form of nitrate, prove beneficial for crops, especially in semi-arid soils, exceeding critical loads becomes a cause for concern (de Vries, 2021; Novara et al., 2020). This imbalance triggers shifts in competition among plant species, favouring fast-growing plants while stifling smaller plants due to limited access to light, ultimately leading to a decline in species richness (Calvete-Sogo et al., 2016). Moreover, the intolerance of most plants to synthetic fertilisers and high nitrogen levels allows nitrogen-tolerant species to thrive, outcompeting more sensitive wild plants and fungi, resulting in reduced wildlife diversity and impaired plant health (Midolo et al., 2019). In certain Mediterranean countries such as Portugal and Spain, intensive livestock production, coupled with the extensive use of manure and synthetic fertilisers, contributes to environmental issues like groundwater contamination with nitrates (Cameira et al., 2021) (see *Section 2.3.2.3*). Nitrogen influx to aquatic ecosystems contributes to algal blooms, diminishing oxygen availability, increasing eutrophication, and disrupting the delicate balance of aquatic life (Ochoa-Hueso et al., 2011; Padedda et al., 2019). Furthermore, contamination with pesticides, herbicides (such as glyphosate), and persistent organic pollutants are also found in high concentrations in soils across the Mediterranean region, affecting ecosystems (Kanakidou et al., 2022; Ochoa-Hueso et al., 2011). Finally, the creation of infrastructure on watercourses and its use for aquaculture or recreational activities has also impacted aquatic ecosystems, often with the introduction of exotic invasive species (IPBES, 2023; Zamora-Marín et al., 2023).

Urban areas compete for space with agroecosystems (housing and infrastructure vs. local food production) as well as with less humanised ecosystems (more pristine). In either case, they induce the fragmentation of habitats and increase pollution in its various forms (chemical, sound, light, etc.). The phenomenon of habitat loss and fragmentation can potentially cause the segregation of extant habitat patches, thereby causing a decline in inter-population connectivity (Pacifici et al., 2015). The transition to sustainable energy forms is not without impact on ecosystem health. Technologies have not yet achieved optimal performance, and often require conversion of land use, in vast areas, resulting in the loss and fragmentation of habitats (see *Section 2.4.2*).

2.5.1.3 Pollution

Pollution in the Mediterranean region yields both direct and intricate impacts on the quality of air, soil, and water, unfolding through diverse pathways that collectively undermine the overall health of ecosystems. Certain air pollutants, such as ozone (O_3) and particulate matter, damage plants. Elevated levels of these pollutants trigger a chain reaction leading to reduced growth rates, accumulation of harmful substances, and adverse effects on biodiversity and essential ecosystem services. Ozone levels surpassing safety thresholds infiltrate plant leaves, impeding photosynthesis and rendering plants more susceptible to pests and diseases (Calvete-Sogo et al., 2016; Monga et al., 2015). Air pollutants can also interfere with the behaviour of pollinators like bees and other insects. This interference may reduce pollination rates, a crucial step in the reproduction of many flowering plants. Additionally, prolonged exposure to high air pollution levels results in the decline of essential nutrients such as calcium, potassium, and magnesium in the soil, disrupting nutrient balance and triggering cascading effects within the intricate web of the ecosystem (de Vries, 2021; Ochoa-Hueso et al., 2011).

The anthropogenic noise generated by diverse activities (e.g. shipping traffic, construction and coastal development, fishing, renewable energy generation, etc.) has altered the quality of the marine environment with consequences on physiology, communication, behaviour, and energetics of different marine species (Abdulla & Linden, 2008; Chahouri et al., 2022; Rako-Gospić & Picciulin, 2019).

There are multiple consequences for soil contamination, impacting soil functions and disrupting crucial ecological functions through a reduction in the abundance of organisms for sensitive species, by reducing their fitness and reproductive ability and increasing their susceptibility to diseases. Additionally, sensitive species will be replaced by more tolerant ones, shifting species composition first (potentially favouring exotics) and decreasing species richness later on, again, with stronger impacts on local system functionality (Branquinho et al., 2019; Ferreira et al., 2022).

Escalation of pollution in the Mediterranean region directly puts its unique habitats and biodiversity at risk, precipitating shifts in the geographical ranges of species and reshaping the dynamics of their interactions (Martínez-Megías & Rico, 2023). These interconnected effects contribute significantly to the detriment of ecosystems, influencing the delicate balance of biodiversity, ecological equilibrium, and the invaluable services that ecosystems provide to communities (Kanakidou et al., 2022). Many species in this region exhibit specific environmental requirements for survival, and when pollution disrupts their habitats, the struggle for survival and reproductive challenges become pronounced (Albano et al., 2021). This disruption has the potential to lead to the loss of entire species or a decline in their populations, particularly impacting those that are uniquely adapted to the Mediterranean's distinct environmental conditions (Albano et al., 2021).

Furthermore, pollution in the Mediterranean alters environmental conditions, including temperature, water quality, and food availability (Papamichael et al., 2022). Sensitivity to these changes compels species to migrate or shift their distribution to more suitable locations. This ecological flux can trigger cascading effects, disrupting the intricate balance between different species and restructuring the communities that characterise the Mediterranean ecosystems. The influence of pollution extends to the behaviour, physiology, and reproductive capabilities of various species in the Mediterranean. These alterations reverberate through the intricate web of species interactions, potentially leading to changes in predator-prey dynamics, competition for resources, and overall shifts in ecosystem functioning (Ochoa-Hueso et al., 2017). Moreover, heightened pollution levels result in diminished productivity. In aquatic ecosystems, water pollution can hinder photosynthesis by marine plants due to reduced sunlight penetration or nutrient imbalances (López-Doval et al., 2013). Similarly, in terrestrial ecosystems, air and soil pollution can inhibit the growth and productivity of plants essential to the Mediterranean landscape (Ferreira et al., 2022). Additionally, pollution weakens the natural defences of organisms, rendering them more susceptible to stressors. Compromising immune systems in plants and animals makes them more vulnerable to diseases. Moreover, pollution can disrupt the abundance and distribution of certain species, paving the way for the proliferation of pests and invasive species and exacerbating the ecological challenges faced by the Mediterranean region. For instance, disease-driven mass mortality events, such as the one affecting the iconic *Pinna nobilis* pen shell in the Mediterranean Sea since 2016 caused by the parasite *Haplosporidium pinnae*, highlight the susceptibility of certain species to diseases (Katsanevakis et al., 2019). Similarly, the mass mortality event of the highly abundant non-indigenous mussel *Brachidontes pharaonis* along the Israeli rocky shore in 2016 underscores the potential impact of unknown causes linked to pollution (Rilov et al., 2020). The interconnected nature of these pollution-induced effects compounds into a cumulative threat to ecosystem health in the Mediterranean. This interconnected cascade has far-reaching consequences, impacting primary producers, herbivores, predators, and decomposers, ultimately leading to an overarching decline in the health of Mediterranean ecosystems.

2.5.2 Cascading impacts of climate-induced ecosystem changes on water, food, and energy

Climate change, through its effects on water availability (air, soil, groundwater, and streams), on temperature extremes (higher maximum and minimum temperatures) and on climatic extremes (heatwaves, flash floods, storms) has far-reaching effects on ecosystem health. These effects manifest in terms of decrease in productivity and decrease in diversity at all levels (intraspecific, species, interactions, and landscape). The noteworthy impact of climate change on the health of Mediterranean ecosystems is evidenced by its effects on their structure, composition, and functioning (see *Section 2.5.1.1*). The perturbations mentioned above have the potential to initiate a cascade of effects throughout the trophic levels, resulting in the destabilisation of ecological dynamics and the impairment of ecosystem functionality (Bagstad et al., 2017). These ecosystem functions change the delivery of several ecosystem services that in turn cascade to the other WEFE components, namely, water availability and quality, food availability and diversity and energy availability (*Figure 2.19*). The benefits that humans obtain from ecosystems, known as ecosystem services, are susceptible to significant effects from climate change. These effects cover the three ecosystem service types: (1) provisioning; (2) regulating; and (3) cultural (*Figure 2.19*).

The decrease in productivity due to climate change negatively impacts several provisioning ecosystem services, as it leads to a decline in the availability of food from wild plants and animals, the reduction of water supply for various human needs (due to less retention at vegetation level), and the reduction of biomass-based energy, resulting in the loss of food availability, water availability and energy availability, respectively.

Decreased vegetation productivity may lead to reduced water retention in the soil, affecting overall water availability in ecosystems (*Figure 2.19*). This reduction in water availability can directly impact water supply for various human needs, including agriculture, industrial processes, and domestic use (MedECC, 2020). Additionally, biomass-based energy resources, such as woody plants, agricultural residues, and organic waste, may experience decreased yields due to low vegetation productivity at ecosystem level (Peñuelas et al., 2017).

Decline in biological diversity, induced by climate change, leads to alterations in species composition, distribution, and abundance, which is critical for maintaining ecosystem functionality (Díaz et al., 2007). Biodiversity loss poses a serious threat to the overall resilience of ecosystems. Diverse ecosystems, with a variety of species, are better equipped to withstand environmental stressors, adapt to changes, and recover from disturbances. Networks of ecosystem functionality are supported by complex relationships existing between different species, contributing to the stability of ecosystems (Leslie & McCabe, 2013). Biodiversity loss also causes changes in trophic webs and interaction between organisms within the ecological system. For example, changes in predator–prey relations can destroy an ecological balance. A decline or disappearance of species is one of the initiators of a chain reaction resulting in increased abundance of others throughout the food web (Schmitz et al., 2004). Impacts are not limited to ecological structures, but further extend to other facets of biodiversity, such as functional diversity and phylogenetic diversity, impacting ecosystem functions and processes (Zhang et al., 2023). Biodiversity loss can substantially impact regulating ecosystem services and negatively affect five categories (*Figure 2.19*): (1) maintenance of soil structure and fertility; (2) decomposition, remineralisation, and recycling processes; (3) pollination; (4) seed dispersal; and (5) pest and disease control, which subsequently negatively impacts food availability (Hanisch et al., 2020). Reduced diversity can also limit the variety of foods available for consumption, affecting both human nutrition and cultural preferences. Changes in the distribution and abundance of plant and animal species decreases the availability of traditional food sources for local communities, such as wild thyme (*Thymus spp.*), wild asparagus, wild artichokes, various wild berries, wild mushrooms, wild game, and edible seaweeds.

Ecosystems are of paramount importance in the preservation of soil fertility and nutrient cycling, which are facilitated by diverse mechanisms, including decomposition. Accordingly, the reduction in biodiversity and degradation of ecosystems can lead to a decline in the supply of these services. Additionally, climate change has the capacity to alter vital ecological mechanisms, such as nutrient cycling, primary production, and decomposition rates, among others. These changes potentially result in a decrease in soil fertility and potential reductions in agricultural productivity, increasing dependence on synthetic fertilisers, thereby expanding associated GHG emissions and soil and water pollution.

Healthy ecosystems are also essential for maintaining soil structure, preventing soil erosion, and consequently reducing water pollution. Examples of species in the terrestrial realm that affect the maintenance of soil structure by anchoring the soil with their root systems, are *Cistus* and *Quercus ilex*. However, changes in precipitation patterns and increased temperatures may affect its distribution, abundance, and health, potentially resulting in

Climate change driver	Organismic responses	Ecosystemics responses	Effects on ecosystem services
Warming	- Fast genetic adaptation. - Metabolomic shift towards activated antistressmetabolic pathways. - Changes in elemental composition of plants. - Morphological and metabolomic acclimatation of plants under moderate warming. - Changes in phenology. - Increase terpene emissions. - The increase of VOCs (Volatile Organicic Coumpounds) will affect the signal effect of these coumpounds for pollinators, thereby influencing their competitive ability.	- Desertification - Asymmetrical adaptation capacity among plant community species drive to changes in species composition at medium and long–term. - Changes in the phenology of plant–pollinators relationships Increase of POPs (persistent organic pollutants) concentrations in environment and organisms. - Transformation of primary POPs to more toxic secondary POPs. - Exacerbation of phenological asynchronies between plants and their pollinators. These climate–induced phenological disruptions may also have unexpected eco–evolutionary consequences, biasing sex ratios in the populations of insect species where sex is determined by temperature. - Shifts of species distribution areas of plants and animais to higher latitudes and/or latitudes	- Decreased provision of several ecosystem services, such as water storing capacity, tituber, mushrooms, tourism, soil conservation. - Less water availability for human activities including food production and recreative services. - Increased land cover not situable for farmland and cropland activities.
Drought	- Fast genetic adaptation. - Metabolomic shifts towards activated anti–stress metaboloc pathways. - Changes in elemental composition of plants. - Morphological and metabolomic acclimation of plants under moderate drought. - Disappearance of less drought resistant species under prolonged drought events and/or chronic drought enhancement. - Changes in palatability in plant tissues. - Changed terpene emissions.	- Desertification asymmetrical adaptation capacity among plant community species drives to changes in species composition at medium and long–term favouring drought resistent species. - Decreases of total ecosystem nutrient content. - Changes of allocation to nutrients from leaves to roots, and from plants to soil. - Decrease in soil mineralization - Increases of more recalcitrant fractions of nutrients and decreases of more labile fractions in soils. - The increasing recurrent wildfires linked to drought have transformed several forested areas to shrublands in the last 20 years, e.g., in southern Portugal. - Reduction of ecosystem capacity to act as C–storage.	- Decreased provision of several ecosystem services, such as water storing capacity, tituber, mushrooms, tourism, soil conservation. - Less water availability for human activities including food production and recreative services. - Increase of land cover not situable for farmland and cropland activities. - Decrease of tourism and hiking. - Losses of biodiversity and ecosystem C–storing capacity. - Loss of soil protection capacity.

Table 2.5 | Main recent findings grouped by climate change driver: (1) responses from organisms; (2) responses from ecosystems; and (3) effects on ecosystem services.
Source: Peñuelas et al., (2017).

increased soil erosion (Raimundo et al., 2018; Sardans et al., 2020).

Changes in the distribution and behaviour of species due to climate change can impact crucial ecosystem services such as pollination and seed dispersal. *Apis mellifera* honeybees play a crucial role in pollinating various crops and wildflowers, contributing to the reproduction of plant species. However, changes in temperature and precipitation patterns can affect the abundance and distribution of floral resources which impact the foraging behaviour and overall health of honeybee colonies, potentially leading to decreased pollination services for crops and wild plants (Bartual et al., 2018). Many bird species in the Mediterranean (e.g. *Sylvia spp.*) are involved in seed dispersal, promoting the establishment of plant populations. In this way they play a role in the regeneration of forests and other habitats that serve as essential food and energy suppliers. Shifts in temperature, precipitation,

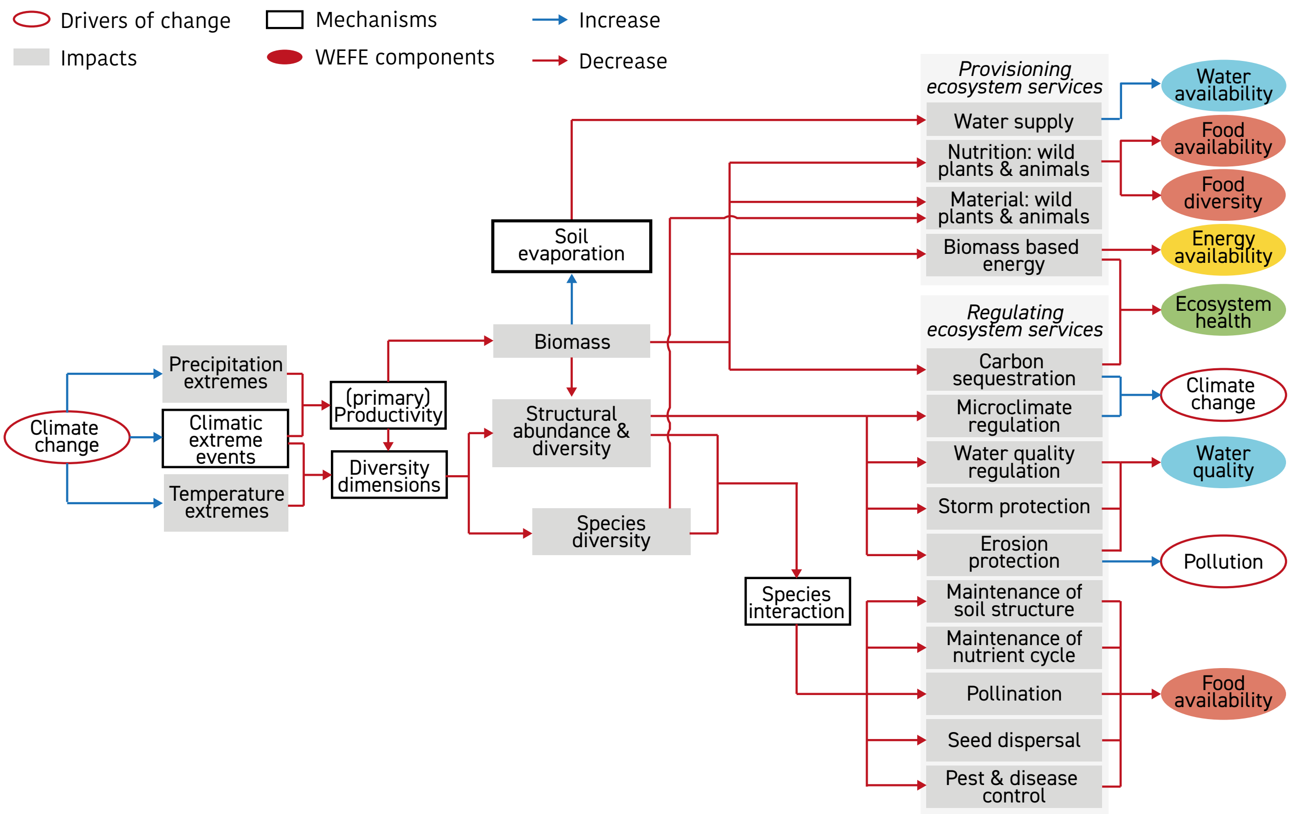

Figure 2.19 | Example of cascading impacts of climate-induced changes in ecosystems health on water, food, and energy, mediated through the impacts on ecosystem services.

and habitat availability can impact the distribution of these bird species which may affect the recruitment and diversity of plant species in the Mediterranean (Rey et al., 2021). European nightjar (*Caprimulgus europaeus*) is an insect-eating bird found in the Mediterranean and contributing to insect control, including nocturnal insects that may be pollinators or pests. Changes in temperature and insect abundance may influence the distribution and behaviour of nightjars, with indirect effects on pollination services through the impact on populations of nocturnal pollinators (Auger-Rozenberg et al., 2015).

Ecosystems in the Mediterranean region have the potential to significantly influence the availability of energy through the provision of renewable energy sources such as biomass, hydropower, and wind energy. As such, changes in ecosystems, including declines in forests or alterations in water availability, can impact the accessibility and durability of energy resources, thereby carrying potential implications for the production and provision of energy (Drobinski et al., 2020a; García-García, 2023).

The decrease in productivity due to climate change also carries some important implications for regulating ecosystem services, as it affects water quality regulation, storm protection and erosion protection. These services, in turn, play a crucial role in influencing and maintaining water quality standards. The protection of watersheds is a notable example that plays a crucial role in the conservation of robust ecosystems, such as forests and wetlands. These ecosystems act as significant controllers of water flow and quality. Wetlands serve as proficient natural filtration mechanisms, regulating the inflow of contaminants, sedimentation, and nutrient leaching into aquatic environments (Cao et al., 2022). Consequently, the degradation or depletion of ecosystems could potentially result in a reduction in water quality, a rise in sediment accumulation, and heightened concentrations of pollutants in aquatic environments. In addition, microclimate regulation and carbon sequestration are both negatively affected by the decrease in productivity, leading to an increase in climate change effects (*Figure 2.19*).

Finally, changes in ecosystem structure and function due to climate change will modify the way we appreciate ecosystems, thereby impacting the cultural ecosystem services that will ultimately affect human well-being (Castro et al., 2011) (*Figure 2.19*).

In general, understanding the interrelationships between ecosystem services and water, food, and energy systems in the Mediterranean region is crucial for the successful implementation of sustainable resource management strategies. The conservation and restoration of ecosystems have the potential to enhance the availability, quality, and resilience of these essential resources, thereby promoting sustainable development and safe guarding human well-being.

2.5.3 Cascading impacts of LULCC-induced ecosystem changes on water, food and energy

From an anthropocentric view, ecosystems provide us with services that are often only noticed when not available anymore. Ecosystem change (mediated by LULCC) will impact on services that cascade into water, food and energy systems. Some examples are described (*Figure 2.20*).

LULCC, resulting from the abandonment of formerly agricultural areas (either caused by land degradation or rural exodus) may take contrasting pathways in terms of ecosystem health. If the rewilding pathway is selected, the loss of direct human food production may be counterbalanced by the increase in regulation services (e.g. pollination), which indirectly benefit other agricultural areas nearby (food availability) and the diversity of wild food sources, including game animals. As the ecological succession proceeds, biomass is produced that (1) covers the soil, reducing surface erosion while biocrusts and the new plants' roots help fixate the soil; (2) biomass above and below ground from plants filters the water and captures micronutrients or even pollutants, improving its quality; (3) more biodiverse plants increase biomass CO_2 fixation, and promote soil organic matter production (and biodiversity), reducing the need for external fertiliser inputs (Oldfield et al., 2019); (4) more organic matter in the soil and more biomass covering the soil, as well as the existence of several strata of vegetation, induces a microclimate that is prone to water retention and protects from aridity, reducing energy (and water) demand; and (5) managed biomass may be used for energy production, although uncontrolled growth can lead to an increase in rural/forest fires. If the abandoned land already has very degraded soil, then there is a less clearly positive trend for the ecosystem. Either the plant cover has difficulties getting established (exacerbating erosion problems) or the species that colonise are inappropriate, in the sense that exotic invasive species may take over more easily due to lack of competition from native species. This may compromise a series of regulatory services based on ecological networks (e.g. food chains).

Industrial agriculture is focused on expanding the areas of monocultures (low biodiversity) which can be easily managed with machinery and with low levels of human labour. Industrial agriculture has to recurrently use agrochemicals (fertilisers, pesticides and herbicides), since natural nutrient cycles are too slow for the high demand and are broken by the overexploitation of natural resources. Excessive use of synthetic fertilisers exacerbates the problem by acidifying soils and disrupting soil health. In addition, the fact that ecological balances between species are missing, facilitates the development of pests and diseases.

Another example (*Figure 2.20*) is the LULCC intensification of agriculture, changing from traditional agricultural forms or semi-natural woodlands, to intensive and industrial, generally monoculture areas. By favouring an immediate increase in food production, ecosystem health is neglected, as well as the long-term productivity and sustainability of the system. Although food availability of one crop is increased (provision services), food diversity and nutritional quality is reduced (Hasanaliyeva et al., 2023) in the cultivated crops, and other sources of biodiverse food (e.g. wild crops and game) are reduced. Intensive agriculture requires the use of irrigation in naturally dry seasons (like the Mediterranean climate has), altering the seasonal patterns of water distribution, and the microclimate for soil microorganisms and decomposition processes (regulation services). Soils forming less organic matter also retain less humidity and need more frequent irrigation, decreasing water availability. Changing to intensive agriculture decreases the soil

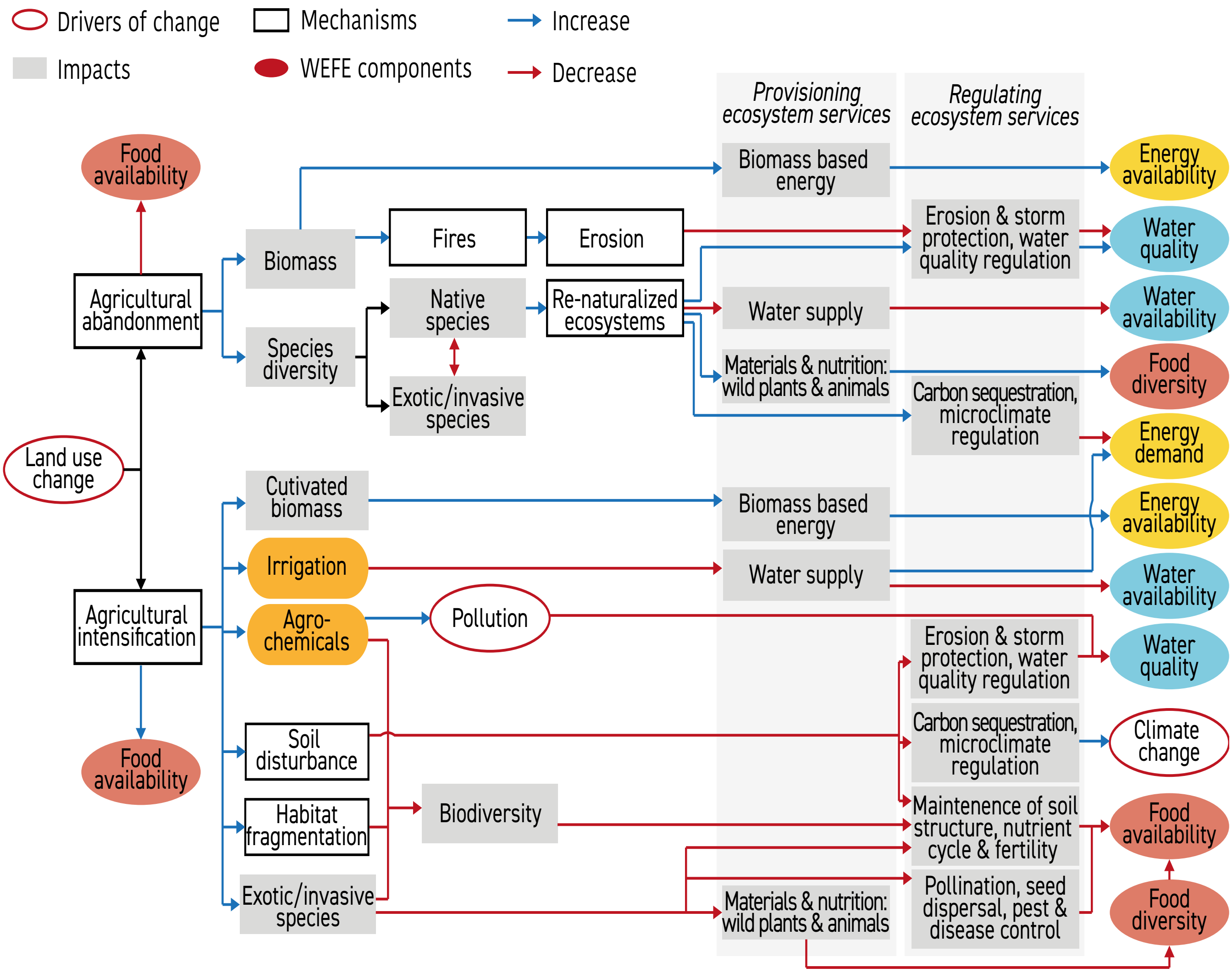

Figure 2.20 | Example of cascading impacts of land use-induced changes in ecosystems health on water, food, and energy, mediated through the impacts on ecosystem services.

biodiversity that maintains soil fertility, from micro– and macrofauna soil engineers (that participate in soil structuring) to microflora decomposers (that maintain nutrient cycles). It also decreases biodiversity above ground, from seed disperser and pollinator species to predators that control the numbers of potentially harmful pests. When the biodiversity of the ecosystem is decreased, it is easier for pests and diseases to get established in the unbalanced network, requiring a higher input of agrochemicals, with impact on water use and quality, energy use and associated pollution.

Changing to an intensive agriculture regime reduces carbon sequestration by reducing soil organic matter. When crops and their residues are removed from cultivation areas, the recycling of nutrients on site is reduced, there is no accumulation of organic matter, carbon sequestration is reduced in the soil, and humidity is not retained, all contributing to climate change.

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WEFE nexus adaptation and mitigation strategies

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Chapter 3
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Executive summary

In addressing adaptation and/or mitigation strategies in the Mediterranean region, a focus on achieving multiple goals across the water, energy, ecosystems and food sectors is imperative. Identifying synergies between these aspects is crucial to avoid negative outcomes and trade-offs. An integrated approach to the Water-Energy-Food-Ecosystem (WEFE) nexus is necessary, one which takes into account its interconnected nature and the potential for rebound effects from addressing individual aspects separately. Because of the region's temporal and spatial variabilities, dealing with the WEFE nexus requires transdisciplinary approaches that incorporate social, political, and governance aspects. In cases of high expected impacts from climate change, transformative adaptation involving significant changes in human inputs and system reorganisation becomes necessary, as incremental adaptations may reach their limits in effectiveness. Watershed management serves as an effective unit for managing the nexus, especially given the Mediterranean region's vulnerability to water stress. The complexity of the region's socio-economic and political diversity necessitates transboundary strategies in adaptation and mitigation efforts, alongside global agreements as a complement to the Paris Agreement. Evaluating adaptation and mitigation strategies in a context-specific manner is essential to ensure effectiveness. While digital and technological solutions, early warning tools, and climate services are valuable, they must be integrated with nature-based solutions, and broad societal understanding and engagement are vital. Despite being solutions, improvements in irrigation techniques can lead to unintended consequences on the WEFE nexus, such as increased water use through the expansion of irrigated surface area and intensity. Embracing behavioural changes, such as reducing meat consumption and food waste, and encouraging restrained consumption and sufficiency, holds high potential for both adaptation and mitigation in the face of environmental challenges.

3.1 Adaptation and mitigation needs for the nexus

The Mediterranean region has a long history of adaptation to harsh environmental conditions, such as hot dry climates and poor soils. This has led to the development of heterogeneous and mixed landscapes and agricultural practices, such as complex irrigation infrastructures and agroforestry systems. However, population growth and climate change have presented significant challenges, leading to an increase of crop production and, in some cases, the emergence of monoculture landscapes with high water and energy demands. These changes have impacted ecosystem services (Caraveli, 2000; Daccache et al., 2014), especially considering the fact that the Mediterranean area is one of the 34 global biodiversity hotspots. This biodiversity has, however, been considerably impacted by human activities. Land use change, both throughout history, but particularly in recent decades, has resulted in considerable changes to species composition (García-Vega & Newbold, 2020). This is particularly concerning, as even ecosystem restoration in such arid environments does not result in recovered ecosystems and has significantly lower biodiversity levels and modified community composition (García-Vega & Newbold, 2020). Technological advancement has made it possible to increase agricultural productivity even more. However, in most cases, a narrow focus on adaptation pursued a single goal of producing diverse food items, many of them exported to countries outside the Mediterranean. This has led to a situation where the primary water user in the region is agriculture (around 80% of water withdrawals, with percentages varying depending on country) (EEA, 2001), leading to negative environmental consequences: water depletion, soil and aquifer degradation, and impacts on terrestrial and aquatic biodiversity (Carrão et al., 2016; Lagacherie et al., 2018; Zalidis et al., 2002). Likewise, measures such as the reuse of treated wastewater for irrigation have been related to some health risks (Kalavrouziotis et al., 2015; Lequette et al., 2020), whereas the increase of irrigation areas and the more widespread use of pesticides and fertilisers to ensure food production in the context of water scarcity, has resulted in surface and groundwater pollution, habitat reduction and biodiversity losses (Bilgili et al., 2018; Hadas et al., 1999; Terrado et al., 2016b). In addition, this has led to high vulnerability to climate change and potentially more severe impacts of droughts and heatwaves in the future, with an increased risk of wildfires (Jones et al., 2020).

Adaptation (i.e. actions that reduce the harm caused by climate change) and mitigation (i.e. actions that reduce the concentrations of greenhouse gases which cause climate change) are widely recognised as two pillars of climate action, and future climate and global change impacts will lead to increased societal demands for Mediterranean ecosystems

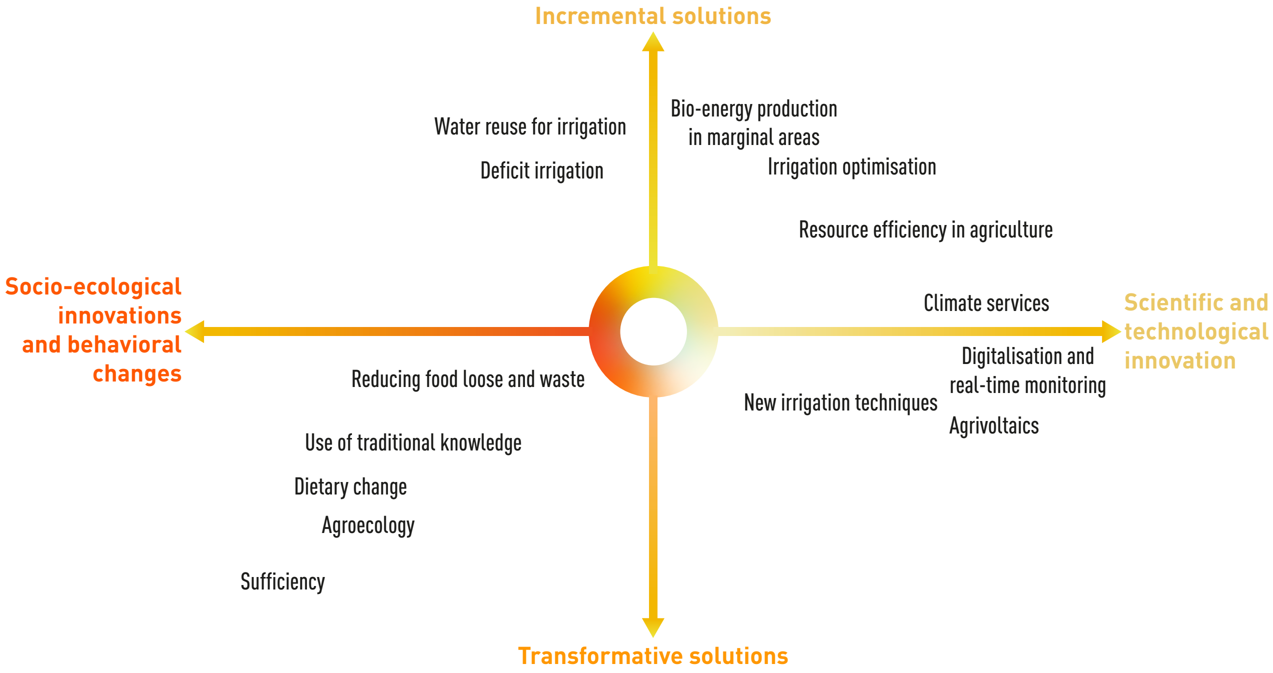

Figure 3.1 | Different gradients of possible adaptation and mitigation solutions for WEFE components used around the Mediterranean region. Adaptation and mitigation solutions range from incremental to transformative, and from socio-ecological innovations and behavioural change to scientific and technological innovation.

to support these actions. The last IPCC report (Begum et al., 2022) states that for adaptation, a solution is an option which is effective, feasible and conforms to principles of justice. From a WEFE perspective, adaptation and mitigation strategies in the Mediterranean need to focus on multiple goals to achieve synergies for water, energy, food and ecosystems. This is particularly relevant for the forestry sector, where promoting fast-growing high wood yield species has led to the spread of non-native tree species (eucalyptus, pine), resulting in negative impacts on biodiversity, water cycles and fire risk. For example, plantations of eucalyptus threaten Mediterranean plant communities, due to the species' rapid growth and encroachment on spatially limited habitats such as riverine vegetation (Badalamenti et al., 2018), and are already spread across considerable portions of protected areas in the Mediterranean, such as the Natura 2000 network on the Iberian Peninsula (Bussotti et al., 2015; Deus et al., 2018). All these examples demonstrate how adaptation and/or mitigation strategies to current and future global changes, particularly in the Mediterranean, need to focus on multiple goals where synergies for the water, energy, ecosystems and food systems can be achieved, or at least trade-offs in other aspects of the WEFE nexus can be avoided. This is particularly valid considering mitigation strategies, as several of them, which can be applied in other bio-climatic regions – e.g. large-scale tree planting – cannot be considered as equally valuable in the Mediterranean area, because of the possible impact on ecosystems and water resources.

Adaptation and mitigation solutions are usually distinguished on a gradient of two main types: incremental and transformative. The first include marginal changes over time within the existing system whereas the second include non-linear changes that fundamentally shift the function and operation of the system (Dilling et al., 2023; Pelling et al., 2014; Wilson et al., 2013). The last IPCC report emphasises the role of transformational adaptation, which changes the fundamental attributes of a socioeconomic system in anticipation of climate change and its impacts (Begum et al., 2022). Transformative adaptation requires increasing human inputs and system re-organisation, but it can be the most appropriate response to climate change and other environmental and human drivers, when the severity of the expected impacts is particularly high, the time available for implementation short due to severe impacts, or when current incremental adaptation options are reaching their limits in terms of implementation and functionality (Fedele et al., 2019). From another perspective, adaptation and mitigation solutions in the WEFE sectors can range from those more related to ecological and consumption-reducing behaviours to those more related to scientific and technological innovation (*Figure 3.1*).

3.2 The WEFE nexus as an approach to optimise adaptation and mitigation across the Mediterranean region

The WEFE nexus approach is proposed for designing better adaptation and mitigation strategies for different drivers affecting the Mediterranean region, including climate change leading to desertification, pollution, population growth, lifestyle changes and urbanisation (see *Chapter 2*). There are different national, regional, and global plans and actions with the objective of mitigating and adapting to the consequences of climate change. Specific strategies have the potential to generate mutually beneficial "win-win" situations in multiple sectors (Mbow et al., 2017). For example, implementing sustainable agricultural practices through soil management can reduce greenhouse gas emissions (benefiting climate) and conserve water (benefiting water). Also, supporting the adoption of renewable energy sources not only provides energy benefits but also mitigates environmental harm (beneficial to ecosystems). However, in some instances and contrary to expectations, sectoral strategies for adaptation and mitigation of climate change may potentially exacerbate adverse externalities and trade-offs within the nexus, as opposed to mitigating them (Mahlknecht et al., 2020). For example, agricultural intensification, hydropower, first-generation biofuels, and the transition to non-conventional water resources do not consistently align with the concept of nexus approach (Giordano & Quagliarotti, 2020). Simultaneously, the production of water, energy and food using business-as-usual strategies (see *Chapter 2*) may increase greenhouse gas emissions, thereby contributing to climate change.

Nexus solutions include a variety of interventions that benefit at least two of the four WEFE nexus sectors while ensuring non-negative or neutral outcomes for all sectors. Unlike other integrated approaches that are the dominant paradigm for integrated management within a particular sector and resource (such as Integrated Water Resource Management - IWRM and Integrated Natural Resource Management - INRM), nexus approaches lead to an integration that cuts across different sectors and resources (Roidt & Avellán, 2019). Likewise, the nexus framework benefits from the incorporation of green and circular economy principles, which involves the use of multi-functional production systems, cross-resources and cross-sector recycling, better able to ensure resource security and sustainable development by reducing waste (Carli & Quagliarotti, 2022; Segovia-Hernández et al., 2023) developing context-specific solutions that also value local knowledge in the implementation of actions. Such solutions can potentially help improve the management of water resources and ecosystems, improve use efficiency, maintain agricultural productivity and biodiversity conservation, and mobilise alternative sources of water and energy to increase their availability and access. By its nature, the WEFE nexus requires integrated technical, natural, social, political and governance aspects (see *Chapter 5*). Most WEFE discussions and applications have been developed so far at national and global level (see *Figure 3.5*), whereas there is a need for more research at local scales, and a diverse and flexible set of evidence-based solutions that can be integrated to maximise the overall resilience of the region. Transdisciplinary approaches are needed for addressing the interlinked temporal and spatial variabilities of the Mediterranean region (e.g. Lucca et al., 2023; Tàbara et al., 2018).

According to the classification adopted by the Climate-ADAPT platform and from the technical report of the European Topic Centre on Climate Change impacts, vulnerability and Adaptation (ETC/EAA, 2021), based on the IPCC (2014) report, adaptation solutions can be classified into three main classes: structural and physical options, social options and institutional options. Since those categories encompass a wide variety of solutions in sectors beyond the WEFE, options that have a direct relation to the sectors and have been implemented in the Mediterranean area have been selected from the categories. Mitigation and adaptation options are therefore organised as follows: technological options, ecosystem-based options (including nature-based solutions) and behavioural change options. Institutional options, including governance and policy, are discussed in *Chapter 5*. Finally, integrated assessments are needed to develop governance strategies for sustainability transitions that include social innovations (e.g. conscious consumption of resources such as water, food or energy) and technical innovations (e.g. renewable energy alternatives, organic agriculture or aquifer recharge) (Halbe et al., 2015). Examples of impacts of policy measures on nexus components include agricultural subsidies that aim to promote the productivity of woody crops, such as olive trees in southern Spain which have led to increased groundwater abstractions for olive irrigation and increased pressure on local groundwater resources (Salmoral et al., 2011). In the case of Egypt, Wichelns (2023) found that when planning which crops to invest in, farmers favoured crops that give a high return on land value rather than on water value, irrespective of there being a better national option to importing virtual water.

3.2.1 Technological options

Technological solutions in the Mediterranean are often related to technical developments for improving water and energy use efficiency as well as increasing the use of machinery to improve labour productivity in food production, although fuel consumption and engine emissions may have negative environmental impacts and could reduce their potential contributions to adaptation and mitigation from a WEFE nexus perspective (Lovarelli & Bacenetti, 2017). Often, different technologies are implemented together, such as protected crop cultivation in greenhouses combined with efficient irrigation and indoor climate control (Imache et al., 2009). It is worth noting that there is a technological gap, regarding modern technologies, between the Northern and Southern Mediterranean, which is expected to grow in several sectors, as well as a gap regarding the vulnerability to climate change, pressure on natural resources and nutritional challenges (Antonelli et al., 2022; Pérez-Castro et al., 2021). Under this category we also find traditional technologies and infrastructure. Below, there is a non-exhaustive list of technological solutions relating to WEFE components that have been applied in the Mediterranean. Given the relevance of water and ecosystems management in the region, irrigation technologies are presented in separate *Section 3.2.1.1*.

Use of renewable energy, alternative energy resources, and improving resource use efficiency in agriculture and other sectors

Renewable energy can play an essential role in meeting the need for electricity in the whole food production chain and transport. Examples include the use of solar energy in desalination plants, the use of renewable energy for wastewater reuse to irrigate crops and decorative plants, electrification of rural areas, improvement of local industrial production (e.g. solar-powered water pump), and provision of electricity to drinking water treatment plants (Malagó et al., 2021). Suitable (but limited to specific areas) geothermal energy can be an important energy resource for electricity generation and is also used directly in heating, food and agriculture, aquaculture and some industrial processes. For instance, it has been used for improving crop production in the Suez Gulf in Egypt (Fahmy et al., 2016). In Tunisia, about 1143 million m³ are exploited from geothermal resources (temperatures between 30°C and 80°C), 76% of which is used for agricultural purposes, 19% for drinking water and 5% for industry and tourism (Ministry of Agriculture and Water Resources General Direction of Water Resources, 2005). Tunisia is one of the leading countries using geothermal water resources for heating plastic greenhouses. In the Kebili region, 98% of geothermal resources are utilised for agricultural purposes (71% for oases and 27% for greenhouses), the remaining part (2%) is used for bathing (hammams), tourism and pools (Ben Mohamed, 2010). Other specific applications for resource use efficiency include improved crop waste management (for example citrus, olives, grapes) through biorefineries. In the driest countries, the potential of renewable energy sources can be expressed mostly at farm/smallholder level, where the energy produced can cut the cost of irrigation and reduce GHG emissions associated with irrigation or biofuels produced on farms to be used by the machinery.

Agrivoltaics (AVs)

Agrivoltaics is a food-energy producing system that involves the simultaneous use of land areas for both solar photovoltaic (PV) power generation and agriculture. Agrivoltaics deployment could lead to significant benefits across the food-energy-water nexus, as it could simultaneously power carbon-neutral farms, allow for more resilient and sustainable agriculture, and support the clean energy transition (Herrero, 2020). However, the development of PV infrastructures necessary to meet carbon targets requires land (see *Chapter 2*) which could conflict with food production. Building PV panels over crop fields can reduce competition between solar and agriculture in land use (Valle et al., 2017), especially in regions characterised by land scarcity, such as small islands, and/or densely populated regions (Amaducci et al., 2018; Dinesh & Pearce, 2016; Herrero, 2020). Furthermore, in dry land environments, this combined use can help mitigate the impacts of climate change increasing land use efficiency and enhancing water management (Al Mamun et al., 2022; Amaducci et al., 2018; Barron-Gafford et al., 2019). PV panels, with their shielding, reduce heat stress and evapotranspiration and can optimise the distribution of solar radiation over crops (Dupraz et al., 2011; Herrero, 2020). This can lead to improved crop productivity and reduced water consumption and soil degradation (Barron-Gafford et al., 2019; Dupraz et al., 2011; Elamri et al., 2018). Moreover, they can protect crops against hazardous events, such as hail and frost which can endanger crop yields (Dupraz et al., 2011; Herrero, 2020). At the same time, PV panels make farms energy self-sustaining and, in these conditions, they even increase their electrical yield (Dinesh & Pearce, 2016), owing to the underlying microclimate and the possibility of modifying their tilt (Valle et al., 2017), both aspects that optimise the working conditions of PV panels. Despite the positive perspectives of installing agrivoltaics systems, there are still issues that need to be investigated, as the benefits may not occur for every type of crop, soil or in every period of the year, and not all the effects of modifying light and water availability, temperature, wind and humidity – the main factors that influence crop productivity – are well known (Trommsdorff et al., 2021).

Digitalisation and precision agriculture

Digital solutions include remote monitoring, digital sensors, artificial intelligence, robotics and internet of things applied to agriculture and resource management for improving efficiency, productivity, product quality and sustainability, through better informed and real-time decision making. Using remote sensing in precision agriculture for irrigation water management can include crop water status monitoring, calculating evapotranspiration, infrared thermography, crop water status, and crop attributes (Samreen et al., 2023). Techniques such as drip irrigation, micro-irrigation, and precision irrigation deliver water directly to the root zone, minimising evaporation and runoff. These methods ensure that water is targeted efficiently, reducing water waste and improving irrigation efficiency (Chai et al., 2016). The agricultural sector has undergone a significant transformation through the adoption of Internet of Things (IoT) technology. This technology gives farmers immediate access to real-time data concerning environmental conditions and machine status. This information can help farmers to enhance decision-making across various facets of their work, encompassing both crop cultivation and livestock supervision. Through the integration of real-time data from IoT with geo-spatial information, farmers can engage in precision farming, leading to increased yields, minimised waste, and the implementation of more sustainable practices. Moreover, IoT technology helps farmers to remotely oversee their crops and livestock, resulting in reduced labour costs and ensuring the well-being and safety of their animals. The main barriers related to the use and application of these new technologies are related to the cost of their adoption and the need for know-how on their use (Fabiani et al., 2020). For this reason, the acceptance of digital assets by local authorities and institutions necessitates a co-production process involving stakeholders and end-users within the social and humanities domains. Reasons for concern regarding these types of technologies refer to (1) data ownership, accessibility, sharing and control, (2) power (re)distribution, and (3) impacts on human life and society (van der Burg et al., 2019).

Early warning systems and climate services

Understanding past, present and future climate, environmental and socio-economic conditions is key to improving the resilience of the WEFE nexus in the Mediterranean region. In this sense, early warning systems, climate services and risk management approaches have shown broad applicability across various sectors in the Mediterranean (Sánchez-García et al., 2022). These approaches, which often rely on Earth Observations and/or modelling systems technologies, can support the improvement of business operations and policy decisions, which need to incorporate a nexus approach. Examples include decision support tools, online platforms, or other products co-developed with users that provide information and services to support their decision-making and co-producing local and regional integrated assessments that fulfil stakeholders' needs. The combination of the nexus approach with climate services and early-warning systems is essential to increase the societal understanding of trade-offs and co-benefits of actual and proposed policies and scenarios (Cremades et al., 2016, 2019). Demand for and supply of this information is growing rapidly, although access is not the same in all Mediterranean countries. In the Eastern and Southern Mediterranean, climate services have complemented the nexus approach, using a set of regional long-term climate model simulations for cross-sectoral impacts of hydro-climatic and socio-economic futures on water resources, habitat for species and food and energy production (Cramer et al., 2018; de Roo et al., 2021; Koutroulis et al., 2016; Terrado, et al., 2016b). Climate services have been used to anticipate climate change impacts on nexus components in Crete (Koutroulis et al., 2016). Using a set of representative regional climate model simulations from the EURO-CORDEX initiative, the study assesses future water availability under a cross-sectoral climate change impact framework. A decrease of local water resources ranging from 20–37% was projected under 2°C of global warming, mainly due to increasing irrigation demand. The study identified the business-as-usual scenario as the least cost-effective, whereas the high sustainability scenario was the most cost-effective option. Climate services across different time scales have been specifically used in agriculture to predict the risk of crop failure, pest damage, and water deficit, as well as natural hazards like heatwaves, droughts and storms, which can simultaneously influence various elements of the WEFE nexus. Examples of climate services focusing on three staples of the Mediterranean food system, i.e. grape, olive and durum wheat, are available for the Iberian Peninsula and Italy (Dell'Aquila et al., 2023; Terrado et al., 2023). While supporting optimal agro-management decisions and activities from sowing to harvesting, such tools take into consideration various elements of the WEFE nexus. Apart from attaining more stable crop yields, decisions therefore also need to address sustainable crop growth, which involves reducing pollution impacts of food production on soils, water and ecosystems as well as optimising the use of irrigation water. Likewise, climate services and early warning systems have also been used for improving water management from an integrated perspective in bassins across the Mediterranean. For instance, seasonal forecasting tools have been applied to assess water allocation for artificial snow and ice-making in Alpine ski resorts, taking into account different stakeholder demands (Hanzer et al., 2020; Sánchez-García et al., 2022). Climate forecasts have also been applied, together with the use of flexible operating policies, to guide reservoir management in the water-stressed Messara valley in Crete (Crippa et al., 2023). Using climate forecasts for reservoir operation was useful for balancing competing demands within the region. To be effective, these tools need to be developed following a transdisciplinary approach, coupling scientific knowledge from various disciplines (i.e. breaking silos) with practitioners' knowledge.

Increase bio-energy crop production in marginal areas

Competition with food production is a common trade-off when producing bio-energy crops, and growing them in Mediterranean marginal areas that are otherwise not used (such as contaminated areas or abandoned ones) would not lead to negative trade-offs with food production (IRENA, 2017). The use of abandoned land for bioenergy production can bring added value, generate new revenue sources for landowners, and stimulate the growth of short bio-based value chains resulting in job creation opportunities (Khawaja et al., 2021). Special care needs to be taken when selecting such marginal areas, first, in defining what is marginal (Csikós & Tóth, 2023), second, to select those most agronomically suitable, and third, to avoid potential impacts on ecosystems and water resources, such as habitat disruption, soil degradation, introduction of alien species and alteration of water balance. Solutions identified as suitable in one region, might be disruptive in other, neighbouring regions, as shown by Núñez et al. (2013) in Spain, where such crops could make sense in the Northeast, but could lead to water conflicts in the south-eastern part of the country. In addition, while studies indicate potential synergies between bioenergy crop production in marginal areas and ecosystem restoration, there is little evidence on how bio-energy crop production could impact different species or landscape connectivity, as it could lead to homogenisation of heterogeneous marginal lands (Pulighe et al., 2019). Furthermore, crops need to be resilient to droughts and have lower water demands. Moreover, a rebound effect can be caused by the use of monoculture on big surfaces, decreasing biodiversity and associated ecosystem services.

Box 3.1

Opportunities using solar energy (innovation) for groundwater pumping in the Kebili Region (Tunisia): new challenges for water resources

In the distant past, traditional oases in the Kebili region (southern Tunisia) were established on artesian springs. Increased adoption of solar-based groundwater pumping is chiefly observed among farmers who are off-grid, in private agricultural extensions that now represent a much larger area than traditional oases. Research revealed that this increase in solar panels plays a growing role in the depletion of groundwater resources (Mekki et al., 2022). In North Africa, discussions are yet to start about how to frame the development of solar panels within a broader perspective, which would make it possible to limit risks (especially groundwater depletion) and tap opportunities (such as "green" production of energy). The challenge is to develop integrated approaches and evaluation tools, in order to characterise and evaluate the public policies and individual adaptation strategies which induce feedback on agricultural production, energy and water use. This would require connections between actors in the agriculture and water sector on the one hand, and energy on the other hand. Addressing groundwater depletion in North Africa has been found to need: (1) better legal and regulatory frameworks (Hartung & Pluschke, 2018) and better implementation of these frameworks; (2) better knowledge of irrigation systems, practices and dynamics of aquifers; and (3) the building of coalitions of actors (Faysse et al., 2018; Kuper et al., 2017). The growing use of solar panels for irrigation would require broadening actions along these three axes, but this time considering the whole agriculture-water-energy nexus. This is urgently needed, as the uptake of solar panels, both for water extraction, as well as for further distribution and irrigation, is likely to expand to all "groundwater economies" in North Africa in coming years (Mekki et al., 2022).

3.2.1.1 Water conservation and irrigation related solutions

Water management for irrigation and related water sources are central to the WEFE nexus in the Mediterranean given the key role of water for food production in the region, where water scarcity is set to be exacerbated with climate change. Given the particularities of the Mediterranean climate, water conservation and irrigation in the Mediterranean has a long history of technological innovations and adaptation measures are common in the region. Before the Roman era, water-harvesting techniques were applied extensively in North Africa (Oweis et al., 2004). Over the centuries, these techniques have improved agricultural production by directing and concentrating rainwater to plants through runoff and have also been used for domestic purposes in dry areas. The following section describes several water management and irrigation options used in the Mediterranean.

Unconventional water resources, improved water use efficiency and reducing leakage

Unconventional water resources, such as desalinated water in conjunction with solar power generation, are expected to play a key role in narrowing the water demand-supply gap (Jones et al., 2019). From a study conducted in Cyprus, the use of concentrated solar power co-generation plants makes it possible to harvest energy and transform it to heat and storage. In this process, the heat released by the turbine and other thermal subsystems can be used to obtain drinking water through desalination (Papanicolas et al., 2016). Moreover, an example of desalination combined with the generation of electricity could be the EcoPeace WEN Pilot Project designed to create a regional desalinated water – solar energy community between Israel, Jordan and Palestine that would result in healthy and sustainable regional interdependencies. Israel and Palestine would produce desalinated water and sell it to Jordan, while Jordan sells Israel and Palestine renewable energy, thereby enabling each partner to harness its comparative advantage in the production of renewable energy and water (Bromberg et al., 2020). Approaches to increase water efficiency, particularly in and close to urban areas, will also be important, but they require a multi-faceted approach that considers factors like population growth, water demand management, infrastructure investment and alternative water sources. Reducing water leakage losses and wasteful use is expected to help stabilise water demand in Mediterranean countries (Burak & Margat, 2016). Many water scarce countries lose considerable amounts of water in the public supply network. This is the case of Italy (leakage losses of 38%), Spain (29%), Cyprus (24%) and Greece (21%). Reducing urban leakage makes it possible to save water that can be used for food, energy production or to maintain environmental flows.

New irrigation techniques

Depending on the region, 33.8 to 46.3% of all water used for irrigation is lost due to inefficient conveying systems or irrigation techniques (Malek & Verburg, 2018). In addition, the vast majority of irrigation in the Mediterranean is still performed using the least efficient technique of surface irrigation (FAO, 2022), which is also the least costly system (Sauer et al., 2010). While uptake for the most efficient technique of drip irrigation is limited both by the need for large investments and the inability to irrigate many staple crops such as cereals, the adoption of sprinkler systems is still low, ranging from 8% in the Eastern Mediterranean, to 30% in the European Union Mediterranean Member States (FAO, 2022). Overall, the Mediterranean region could save 35% of water resources by using improved irrigation techniques (Fader et al., 2016). Modernisation of irrigation systems using water– and energy–saving technologies (e.g. sprinkler system, drip irrigation) can help in saving water resources and increase food productivity. These improvements are especially relevant in the Southern and Eastern Mediterranean, so as to compensate to some degree for increased water demand due to climate change and population growth. However, the use of new irrigation techniques in Libya led to soil salinisation, lowering of the water table, and increasing the amount of energy used (Al–Samarrai & Sadeg, 2020). The energy supply for irrigation generally evolves from pump units consuming diesel to modern pumping stations supplied by the electricity grid or solar energy. Focusing on only ensuring additional water resources and improving efficiency, without actions to improve water extraction and use, or reducing use, could lead to rebound effects due to more cost-efficient irrigation (Jensen, 2007) and thus impact the other WEFE components. In many case studies, an increase of irrigated surface areas, a change towards more water-intensive export crops, or an intensification of agricultural practices have been observed following the acquisition of water-saving irrigation techniques (Venot et al., 2017), for example in Morocco, in the area of Ain Chegag, Bitit, Guerdane, Issen and Lamzoudia (Hoff et al., 2019), resulting in maladaptation. This is particularly important because, under some global change scenarios, south-eastern Mediterranean countries are expected to be unable to cover irrigation demand by the end of the century (Fader et al., 2016, 2020). Given the high investment required to incorporate these systems, they can also result in small–scale farmers abandoning agriculture in favour of large-scale farmers and increasing inequality between these two social groups (Albizua et al., 2019).

Deficit irrigation

Deficit irrigation involves intentionally applying less water to crops than their full water requirements, and in particular concentrates the application of limited seasonal water supplies on moisture-sensitive crop growth stages to maximise the productivity of applied water (Schaible & Aillery, 2012). This approach aims to optimise water use efficiency and address water scarcity challenges while still maintaining acceptable crop yields or even improving yields, for some crops in some contexts, presenting a low-cost solution to reducing water use (Geerts & Raes, 2009). « There are several deficit irrigation solutions. (1) Implementing water-efficient irrigation techniques such as drip irrigation, micro-irrigation, and precision irrigation deliver water directly to the root zone, minimising evaporation and runoff. These methods ensure that water is targeted efficiently, reducing water waste and improving irrigation efficiency (Chai et al., 2016). (2) Deficit irrigation involves carefully managing crop water stress levels to balance water availability with crop needs. By monitoring soil moisture levels and crop water requirements, irrigation can be applied strategically to maintain a certain level of water stress without severely impacting crop productivity. This approach requires a thorough understanding of crop water requirements and the stage-specific sensitivity of different crops to water stress. These methods include partial root-zone drying (Iqbal et al., 2020). (3) Choosing crop varieties that are more tolerant to water stress and have a higher water use efficiency is crucial for deficit irrigation, using traditional ancient varieties or new ones, which are adapted to limited water availability, have deeper root systems, and exhibit higher drought tolerance. These traits enable crops to withstand water stress conditions and maintain acceptable yields with reduced irrigation. (4) Accurate irrigation scheduling is essential for deficit irrigation. Monitoring soil moisture, weather conditions, and crop growth stages can help determine the optimal timing and amount of water to apply.

Water reuse for irrigation

There is high potential for water reuse in irrigation, which is already taking place across many parts of the Eastern and Southern Mediterranean (Elbana et al., 2017; Tal, 2016). In recent decades, the spread of treatment plants has allowed treated water reuse to become a relevant source of water for agricultural production, as irrigated areas continue to expand. However, a systemic evaluation of real performance of many treatment plants or disinfection technologies has not been undertaken and relevant information such as maintenance, costs, and safety are not available. The reallocation that water reuse entails is often innocuous, when wastewater is highly diluted in a river before being reused downstream. But it can be more contentious when wastewater is either already reused directly (typically informally), or when it plays a major support role during periods of low river flow (Ait-Mouheb et al., 2020). Water reuse quality is influenced by factors like source control, sewage system type, treatment, operation, storage, and distribution. Control measures ensure treatment reliability and good operation, while appropriate management of industrial wastewater discharge reduces toxic risks. Microbiological parameters are crucial. Water reuse's impact on agricultural soils must be carefully planned to avoid negative impacts on ecosystems and other WEFE aspects (Levy et al., 2011). This is mostly due to the potentially hazardous properties of water: nutrients (mainly nitrogen and phosphorus), dissolved salts (sodium, boron, etc.) and other constituents such as heavy metals that may accumulate in the soil over time (Levy et al., 2011). Salts may accumulate in the root zone because of the absence of leaching. Over time, the absence of leaching may have harmful impacts on soil biological and chemical activity and hence on crop yields. The problem of soil salinity and sodicity can be solved by increasing soil mineral retention capacity through the application of soil conditioners – natural (manure, compost) or artificial (for example polyacrylamide compounds (Green & Stott, 2001)). In addition to the accretion of salts and nitrates, irrigation with recycled water can, under certain conditions, transfer pathogenic bacteria and viruses to groundwater, i.e. in karst systems, potentially impacting ecosystems. Nonetheless for agriculture, it can also be advantageous. In a controlled experimental system under semi-arid conditions in Sicily, recycled water increased tomato yield by 20% compared with crops using conventional water (Cirelli et al., 2012). In field sites located in Murcia, south-eastern Spain, for lemon trees, the benefits of using recycled water for irrigation are increased soil nutrients, increased crop yield and reduced doses of fertiliser (Pedrero et al., 2010). Nutrient loading from every 1000 m³ of recycled water range from 4 to 24 kg of phosphorus, 16 to 62 kg of nitrogen, 2 to 69 kg of potassium, 18 to 208 kg of calcium, 9 to 110 kg of magnesium and 27 to 182 kg of sodium (Qadir et al., 2007). However, depending on the level of wastewater treatments, some drawbacks are also evident, and include soil salinisation, contamination of sensitive vegetable crops by pathogens, and loss of soil infiltration capacity (Pedrero et al., 2010).

Ancient irrigation systems in the Mediterranean

The recurrent droughts that characterise the mediterranean climate have resulted in the development of a multiplicity of efficient ancient systems for collecting and conserving water for irrigation. As an example, the main water-harvesting techniques encountered in Tunisia can be subdivided into three major groups (Oweis et al., 2004): (1) runoff water harvesting that makes use of runoff as it is collected, thus eliminating the need for storage. These systems include the related micro-catchment techniques called *meskat* and *jessour;* (2) floodwater harvesting and spreading or spate irrigation using diversion dykes *(mgoud)*; and (3) runoff water collection and storage in reservoirs of variable capacities, which provides drinking water for people and animals, as well as water for irrigation. The *khettara* system, a centuries-old traditional canal system in Morocco, was used for groundwater drainage in oasis areas. It captures water from the groundwater table and plays a crucial role in agriculture (El Khoumsi et al., 2017). Indeed, many of these systems are developed together with specific agricultural practices. This is the case of the *navazo* system, used throughout south-western Spain, the *masseria* in Portugal and the *mawasi* in the Middle East. It is an ingenious system in which interconnected cultivated areas are established between dunes. Crops are planted in areas where the water table is close to the surface, meaning water is supplied by capillary action and tidal forces (Sánchez & Cuellar, 2016). The energy efficiency of this system and the way it is integrated into the natural environment make it an interesting example of an inherited agro-ecosystem and a sustainable agriculture model. Despite their importance and WEFE nexus potential, many of these systems are under threat due to loss of functionality, agricultural intensification and urban development pressures (Martínez-Fernández et al., 2013). Development programmes aim to preserve this ecological and socio-cultural heritage that has proven its resilience in the context of climate change. Traditional water management systems are essentially socio-technical systems that can only operate within their proper social context. Changes in practices are therefore not enough but need to be accompanied by deeper changes and new development paradigms. They contribute to soil conservation, traditional landscapes and cultural heritage to build living and resilient ecosystems, and to adapt to climatic changes (Barontini et al., 2017). They also contribute to societal awareness and the recognition of the great diversity of cultural and social values water has to human civilisation, especially in the MENA region (Berndtsson et al., 2016), in order to both preserve natural resources and ensure social equity in access to water.

Box 3.2

The reuse of wastewater: some examples from the Mediterranean region

In Jordan, 87% of safely treated wastewater is now reused directly or with little dilution as water for irrigation. Israel, where treated wastewater accounted for 40% of all water used for irrigation in 2011, and to a lesser degree Tunisia, where about 25% of treated water is now reused, have become recognised leaders in this rapidly expanding field (Kellis et al., 2013). Israel, in particular, uses more than 300 million m^3 yr^{-1} of tertiary-treated effluents or secondary chlorinated effluents in agricultural irrigation, mainly for industrial crops, cotton and fodder, citrus trees, and cooked food and unrestricted irrigation crops (Karnib, 2016). To put this volume into perspective, it represents about 40% of the total amount of treated water used in the whole European Union. However, despite recent improvements, wastewater treatment is still far from being universal in the MENA region. For example, it is estimated that only 8% of the wastewater generated in Lebanon is treated. About 11% of the population benefits from safely managed wastewater systems in the northern and southern governorates, compared to only 7% and 3% in Greater Beirut and Bekaa, respectively (Karnib, 2016). This calls into question the possibility of planned water reuse under national regulations. As a consequence, a wide array of reuse methods exist that range from unplanned, small-scale use of raw wastewater for vegetable production in peri-urban areas of Algeria, Egypt or Morocco to the sophisticated use of ultra-purified water for sensitive crops such as vegetables in Italy. Across the Mediterranean there are examples of all types of reuse levels, from no treatment at all to tertiary treatment. The recently established Bahr El Baqar wastewater treatment plant in Egypt treats the raw drainage water from the Bahr El Baqar Drain (capacity of 2 billion m^3 yr^{-1}), contributing to the cultivation of about 92,000 hectares. The plant will produce 5.6 million m^3 day^{-1} of irrigation water and sludge using solar drying facilities with an annual capacity of 165,000 tonnes at 75% dryness level (Abdel Monem et al., 2022).

3.2.1.2 A WEFE analysis of irrigation options

While the WEFE nexus has been widely proposed to address sustainability challenges in the Mediterranean region (e.g. Saladini et al., 2018), it remains unused when it comes to adaptation in the region. While the rare existing approaches are limited to case studies on a field level (e.g. Fabiani et al., 2020), cross Mediterranean analyses of adaptation in irrigated systems reveal that the WEFE approach has high potential for ensuring sustainable and just outcomes of adaptation in the region (*Figure 3.2*). At the same time, neglecting the WEFE nexus can lead to negative outcomes for other aspects of the nexus, in particular ecosystems.

Across the region, farmers have been adapting their farm practices by improving irrigation efficiency, reducing water use per unit of crop produced, or to deal with water shortages. While the resulting impacts on improved irrigation efficiency and water footprint of produced crops are widely known, potential co-benefits and trade-offs for other aspects of the WEFE nexus (other than water) are less obvious. At farm level, focusing only on the water aspect of the WEFE nexus for adaptation to irrigation systems can lead to undesirable negative trade-offs on other aspects of the nexus, but also on water itself (*Figure 3.2*). Improving irrigation efficiency can increase energy use, impact crop quality, increase salinisation and ecosystem stress, and negatively

NEGATIVE IMPACTS ACROSS WEFE		POSITIVE IMPACTS ACROSS WEFE
	WATER	
8	GROUNDWATER TABLE	1
4	WATER AVAILABILITY	4
2	WATER QUALITY	2
9	SALINISATION	3
11	WATER USE	7
	ENERGY, RESOURCE USE AND INCOME	
4	ENERGY USE	2
1	FARM INPUT USE	5
1	COSTS	4
3	INCOME	11
	FOOD	
5	CROP YIELDS	24
4	QUALITY	4
5	EFFICIENCY	8
	ECOSYSTEMS	
8	SOIL EROSION	3
N/A	SOIL NUTRIENTS	3
4	ECOSYSTEMS STRESS	8
8	LAND USE INTENSITY	4

Figure 3.2 | A summary of observed impacts across the WEFE nexus from a recent review of implemented adaptation in Mediterranean irrigation. The left-hand column shows how improving irrigation by only addressing the water aspect of the WEFE nexus can lead to negative outcomes across WEFE components, and the right-hand column shows the observed positive impacts. The values are a percentage of 142 reviewed studies on farm level adaptation across the whole region.
Source: Harmanny & Malek (2019).

impact the groundwater table. Conversely, achieving co-benefits for other parts of the WEFE nexus is possible and considering them while planning adaptation measures can lead to better outcomes. As an example of these mixed effects of improving irrigation efficiency on different aspects of the WEFE nexus, the modernisation of Spanish irrigation has reduced water use per hectare, but total water use has remained stable (and increased in certain regions). Increased efficiency was offset by the expansion of irrigated area, and energy use greatly increased, as well as GHG emissions due to energy use, infrastructure construction and maintenance, and methane emissions from water bodies (Aguilera et al., 2019). This clearly shows that only focusing on one aspect when adapting to climate change, such as improving water use efficiency, can potentially degrade other issues of the WEFE nexus, such as increased energy consumption and negative impacts on ecosystems due to water use.

3.2.2 Ecosystem-based approaches

The IPCC (2014) included within ecosystems-based approaches a diversity of options such as ecological restoration, including wetland and floodplain

Typology	Examples of NbS	Contributions to WEFE nexus	Reference
WATER	Constructed wetlands	Water purification, flood protection, wildlife support, and recreation	Liquete et al. (2016) Matter & Gado (2024) Saquib et al. (2022)
	Utilisation of permeable surfaces	Improve tree health and enhanced delivery of ecosystem services	Fini et al. (2017) Jessup et al. (2021)
	Green roofs and trees	Assess information on the performance of green infrastructure to moderate urban surface runoff and increase biodiversity	Cristiano et al. (2021) Zölch et al. (2017)
	Straw mulch	Decrease runoff, erosion, and soil loss rates due to the expansion of drip irrigation	Bogunović et al. (2023) Keesstra et al. (2019) Rodrigo-Comino et al. (2019)
	Reconstruction of the homonymous artificial reservoir	Improve crop yield production and agricultural income, secure water supply, and groundwater resources	Panagopoulos and Dimitriou (2020)
	Rain gardens	Stormwater management and generate impact on water runoff and catchment in cities	Koppelaar et al. (2021)
ENERGY SECURITY	Biomimetic architecture	Achieve sustainable and energy-efficient design for reducing urban heat islands and increase the comfort of living	Bar-Cohen (2011) Mirzaei (2015)
	Waste-to-energy	Waste management, energy union, and climate change	Jouhara and Malinauskaite (2019)
FOOD SECURITY	Urban and peri-urban agriculture	Ten key challenges: climate change, food security, biodiversity and ecosystem services, agricultural intensification, resource efficiency, urban renewal and regeneration, land management, public health, social cohesion, and economic growth	Artmann and Sartison (2018) Filippini et al. (2018) Soulard et al. (2017) Viljoen and Bohn (2014)
	Perennial grains	Locate areas for sustainable land management strategies	Peter et al. (2017)
	Organic farming	Minimise environmental impact and enable producers to earn a decent living	Eyhorn et al. (2019) Muller et al. (2017) Muneret et al. (2018)

Table 3.1 | Schematic diagrams of water, food, and energy-related NbS intervention typologies.
Source: Yuan et al (2022).

conservation and restoration; increasing biological diversity; afforestation and reforestation; bushfire reduction and prescribed fire; controlling overfishing; fisheries co-management; assisted migration or managed translocation; ecological corridors; ex situ conservation and seed banks; community-based natural resource management; adaptive land-use management; and green infrastructure. Several of these options currently come under the most recent concept of nature-based solutions, or in the case of food, agroecological approaches, which can play a prominent role in Mediterranean ecosystems.

3.2.2.1 Nature-based solutions

Nature-based solutions (NbS) are solutions inspired and supported by nature which are cost-effective, simultaneously provide environmental, social and economic benefits, and help build resilience (European Commission, 2024). Moreover, according to the IUCN, NbS are "actions to protect, sustainably manage, and restore natural and modified ecosystems, that address societal challenges effectively and adaptively, simultaneously benefitting people and nature" (IUCN, 2016). NbS are highly important in terms of water, food, energy and ecosystems (Yuan et al., 2022) (*Table 3.1*). In general, the possible strategies defined under the umbrella of NbS imply the implementation of blue and/or green infrastructure. The bulk of examples found in the literature fall in the latter category and include green roofs, green walls, woodland-like structures, urban grasslands and meadows, urban scrubland and heathland, horticultural gardens, vegetated filter strips, swales, constructed wetlands, restored wetlands, restored ponds and bioretention basins.

One promising NbS in urban contexts are green roofs, as they can help to fight against climate change effects, and particularly heat stress of the Mediterranean population (Cristiano et al., 2021). Experimental results in Mediterranean cities show the potential of green roofs to reduce energy demand and storm water runoff, although runoff reduction is lower during high precipitation periods (Fioretti et al., 2010; Maiolo et al., 2020). In addition, green roofs contribute to the restoration of Mediterranean vegetation in the urban environment, increase biodiversity, improve air and water quality, and add aesthetic value to the city (Benvenuti, 2014; Cristiano et al., 2021). *Table 3.1* contains a list of contributions to different components of the nexus provided by different NbS, which are classified according to their main contribution either to water, energy or food security. Although the table presents positive contributions, some trade-offs may also occur for some NbS. An example would be organic farming, which may result in lower yields for monocultures in some contexts but minimises environmental impacts while enabling producers to earn a decent living. As found in some studies comparing organic and conventional agriculture in the Mediterranean area, the main objective of sustainability should be the balance between input management, food production, and services provided by agroecosystems, rather than solely the attainment of high yields (Ioannidou et al., 2022; Litskas et al., 2019).

3.2.2.2 Agroecological approach

Mediterranean farming has coevolved with harsh environmental conditions creating an abundant heritage of traditional knowledge for managing agroecosystems. An agroecological approach to agriculture is founded on the integrated application of scientific and traditional knowledge to design agricultural and food systems that work with nature in order to protect the environment and develop resilient, safe, accessible and just agrifood systems. Agroecology is founded on systems thinking so it considers the whole food system, highlighting the role of reconnecting food production and consumption associated with the recovery of the locally adapted, largely plant-based Mediterranean diet (Aguilera et al., 2020; see *Section 3.2.2*). Agroecology therefore provides a nexus entry-point for agricultural management, since a WEFE response through food needs to explore synergies between responses on both the production and consumption sides. Changes in agricultural management practices that follow an agroecological approach at farm level, like intercropping, conservation tillage and organic fertilisation can benefit both soil quality and soil fertility and generate some positive interactions with other WEFE components (Ioannidou et al., 2022; Morugán-Coronado et al., 2020), including biodiversity conservation, efficient water use, water conservation and reducing energy dependency (e.g. through elimination of chemical fertilisers). Conservation tillage practices, including no-tillage and reduced tillage, significantly promote carbon sequestration in Mediterranean agroecology. Combining organic

Box 3.3

Effect of applying technical and ecosystem-based adaptation solutions to the provision of ecosystem services in the Llobregat river basin

In the context of the Water Framework Directive, EU regional river basin authorities are required to propose a list of management actions or measures to be included in the River Basin Management Plans (RBMPs) with the aim of attaining a good ecological status of water bodies. The effect of a number of selected management actions proposed in the RBMP for the Llobregat river basin (Spain), on the provision of ecosystem services in the basin was assessed (Terrado et al., 2016a). The Llobregat basin is typical of semi-arid conditions and constitutes an example of a highly populated, highly impacted and severely exploited area in the Mediterranean region. It is the main water source for Barcelona and its metropolitan area, with a population of more than 3 million people. Although the main aim of the application of management measures is to attain a good ecological status (related to the ecosystem's health), these measures also need to consider other sectors and uses co-existing in the basin, such as water provision for agriculture, drinking, industrial use or energy production. In other words, the measures need to be established considering a nexus perspective.

The regional basin authority proposed 18 measures, including environmental river flows, river connectivity improvement, urban wastewater treatment, and saline pollution reduction. These four measures were selected since they are illustrative of the most commonly applied management actions in European basins (EEA, 2011). The measures had positive and negative impacts on ecosystem services and WEFE nexus components. For instance, the improvement of wastewater treatment also improved surface water quality. This is important since the river receives the discharge from several urban and industrial wastewater treatment plants, especially downstream, where there is a higher concentration of population. Also, the implementation of environmental flows in the upper basin improved ecosystem status, since they ensured suitable water levels for ecosystems, but caused losses in hydropower production and water availability for industry, drinking, and irrigation (*Figure 3.3*). Actually, the basin has several small hydropower plants that take water from the river, routing it through derivation channels to the plants and returning it to the river after several metres. Therefore, environmental flows can compromise the amount of water that can be derived for hydropower production, especially in periods when water levels are low. The identified trade-offs reveal that management actions designed to improve ecosystem status can also have detrimental effects on other components of the WEFE nexus that need to change, if not structured and implemented on a nexus basis.

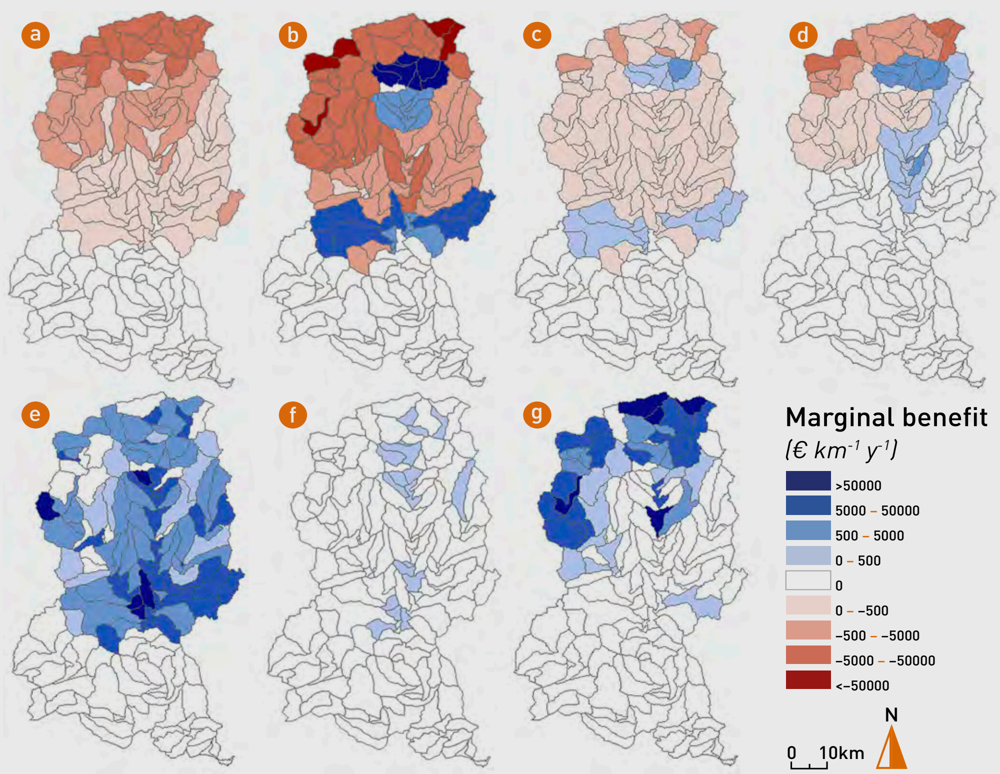

Figure 3.3 | Effects of the establishment of environmental river flows in the upper Llobregat basin on the potential benefits for hydropower production (a), water for drinking (b), water for irrigation (c), water for industry (d), environmental/social benefits (e), existence/conservation of species diversity (f) and enjoyment of recreational areas (g). Results are expressed as marginal values in € per kilometre of river per year. More details in Terrado et al. (2016a).

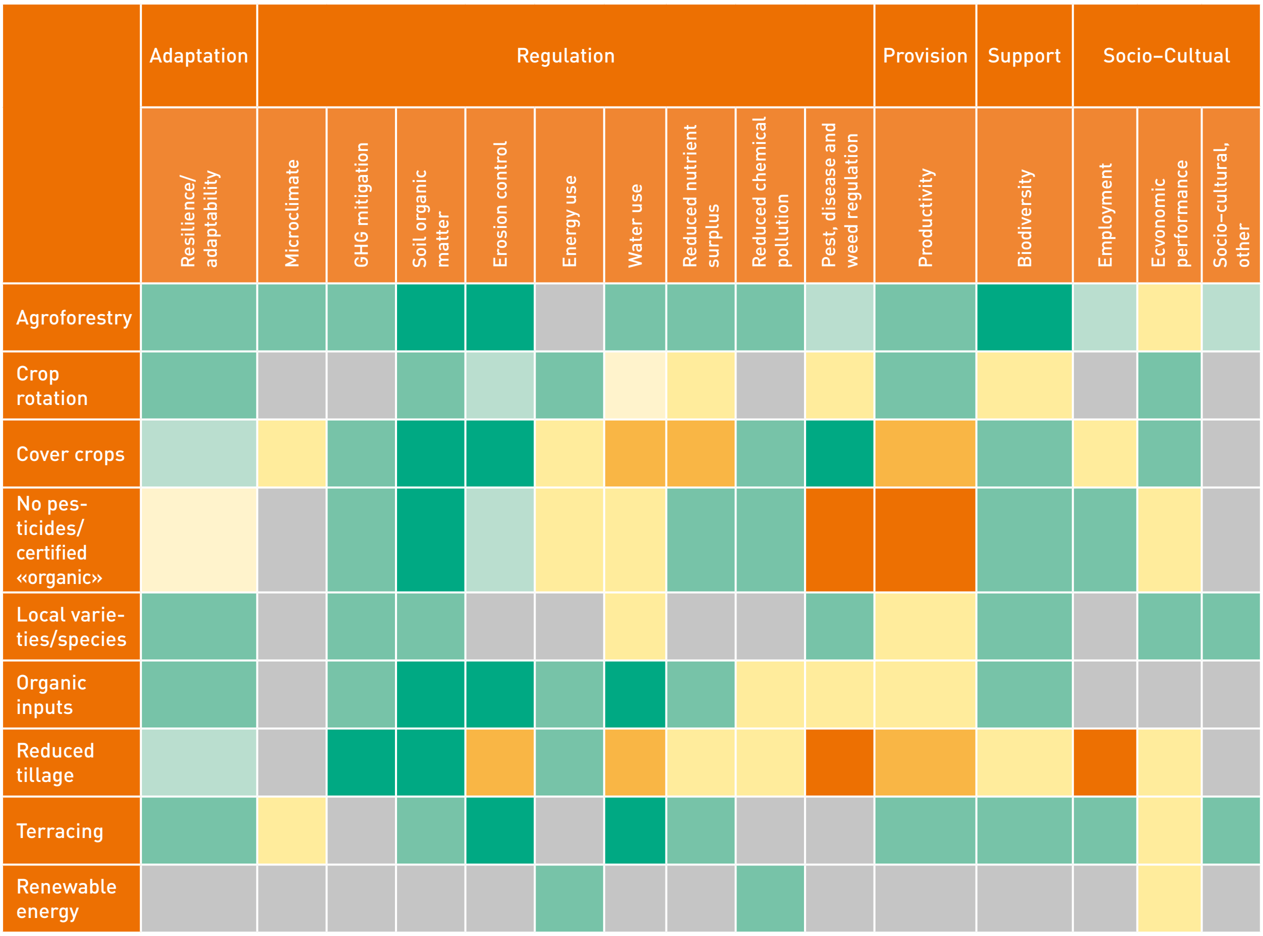

Table 3.2 | The performance across the WEFE nexus of selected agroecological practices in crop production under Mediterranean conditions. Green cells represent generally positive responses (>75% positive), red generally negative ones (>75% negative), yellow mixed or neutral ones, and grey lack of data. Darker colours represent data from meta-analysis of Mediterranean climate studies, medium colours represent evidence from non-systematised field studies in Mediterranean areas, and light colours represent evidence from non-Mediterranean climate areas. Refer to Aguilera et al. (2020) for details of the analysis.

amendments with cover crops or conservation tillage shows good performance in carbon sequestration. At landscape level, agroecology considers the positioning, quality and connectivity of fields and semi-natural habitats. The spatial and temporal organisation of semi-natural elements and the crop mosaic interact (Jeanneret et al., 2021). Such mosaic land systems can therefore also address restoration needs, and adaptation to new climate realities, such as more frequent heat and water stress (Aguilera et al., 2020). Agroecology adaptation to climate change in the Mediterranean involves biodiversity and crop diversity management, increasing soil organic matter (that also reduces soil erosion), reducing fossil fuel dependence, managing extensive herds, using local breeds, and implementing pasture and forage management. These practices enhance adaptation to climate change and ecosystem services related to food production and consumption (*Table 3.2*). Agroecological practices' focus on soil conservation contributes to water conservation, facilitates the sponge effect and thereby reduces water needs for farming.

Agroforestry is an agroecological practice that has a positive effect on crop adaptability, productivity, reduced water use, biodiversity, and other environmental indicators, although there is no available evidence regarding energy use. The experimental assessment shows how the use of agroforestry or mixed forestry/agricultural production can improve the carbon balance, increasing overall carbon storage (Jha, 2018). Organic fertilisers reduce energy and water use and promote biodiversity but have mixed effects on productivity measured in kg ha^{-1}. In general, the short-term negative impacts on crop production measured in kg ha^{-1} (as opposed to number of people fed per hectare) are a common problem for agroecological practices, although yields may benefit in the long term from the positive effects of soil organic matter increase, which are significant in the low organic matter soils found in the Mediterranean (Oldfield et al., 2019).

3.2.2.3 Forest management: reforestation, afforestation and extensive livestock farming

A considerable proportion of Nationally Determined Contributions (NDCs) of Mediterranean countries to mitigate climate change relates to the land use sector, in particular forestry. Countries have pledged to reforest, afforest or restore massive amounts of land to capture and store carbon, while at the same time achieving other nexus co-benefits, such as desertification or soil degradation prevention. In fact, afforestation and carbon accumulation in forests have been ongoing in most of the Mediterranean basin since the mid or late 20th century, due to the combination of land abandonment and fire suppression policies (Martínez-Valderrama et al., 2021; Șahan et al., 2022). Nevertheless, evidence suggests that particularly in the Mediterranean, these large-scale mitigation solutions (with otherwise high potential for adaptation) have to be planned carefully. Numerous case studies across the region demonstrate increased fire risk and decreased biodiversity due to fire suppression policies and the promotion of fast-growing forest plantations (with notable examples of Eucalyptus and Pine plantations in the Iberian Peninsula) leading to continuously forested areas (Ojeda, 2020). Indeed, while fire suppression policies have been effective in decreasing short-term fire (Boccard, 2022), they may have also increased the long-term risk of mega-fires with more devastating consequences, as has been observed in Mediterranean areas of France (Curt & Frejaville, 2018), Portugal (Oliveira et al., 2017) and Greece (Sarris et al., 2014) or impacts on water resources. These trends in forest management combine with climate change to increase fire-related risks. Climate change is already affecting fire severity, as has been observed in Portugal (Turco et al., 2019) and is expected to further increase wildfires in Mediterranean Europe (Dupuy et al., 2020). In addition, the combination of fire with climate-change related events such as extreme rainfall could enhance other impacts such as soil erosion (Morán-Ordóñez et al., 2020), further underlining the need to reduce fire risks. Moreover, most of the focus is on short-term forestry goals, such as quick carbon storage or high timber yields in short rotations. Long-term consequences on the wider WEFE nexus, such as water availability or species composition and biodiversity are mostly not evaluated, meaning that these actions could, in fact, fail to contribute to adaptation over the longer term (Vilà-Cabrera et al., 2018). Another review has identified extensive livestock farming in partially open landscapes as the best way to reduce fire risk while also increasing biodiversity and improving landscape organisation and flows between its components (García-Ruiz et al., 2020), and later studies are exploring different management techniques involving the use of extensive livestock farming (Ameray et al., 2022; Nuss-Girona et al., 2022; Schlickman & Milligan, 2022) and prescribed fires (Davim et al., 2022; Fonseca et al., 2022) for wildfire management in Mediterranean areas. In fact, reductions in the amount of combustible material, fuel load, and biomass, as well as a decline in the frequency of fires exceeding one hectare, were noted. Furthermore, the clearance of shrubland and extensive livestock grazing yielded additional environmental advantages such as mosaic landscapes and enhanced ecosystem services (Lasanta et al., 2018), whereas land abandonment with the related rewilding and consequent accumulation of biomass in unmanaged forests are among the most significant causes of higher fire density and severity, economic damage, and land degradation (Colantoni et al., 2020). In this sense, agroforestry has been identified as one relevant option for reducing wildfires in Mediterranean regions (Damianidis et al., 2021). Moreover, extensive livestock farming at correct density, can improve biodiversity conservation (Broom et al., 2013) and agroecological transition (Aguilera & Rivera Ferre, 2022). Overall, a new consensus is building up advocating for a deep transformation of forest policies away from fire suppression and mono-specific productivity-oriented measures and towards more interdisciplinary and participatory approaches involving "fire coexistence" and multifunctional management of forests (Moreira et al., 2020; Otero & Nielsen, 2017; Stoof & Kettridge, 2022; Wunder et al., 2021), thus simultaneously addressing all the components of the WEFE nexus. For example, in a modelling study, Miezïte et al. (2022) estimated that strategies aimed at minimising forest vulnerability to drought were the most effective in preventing crown fires while also performing well in timber provision and water supply. Likewise, agroforestry systems within an integrated land management approach have been proposed as "productive fuel breaks", to reduce fire risks while recovering rural activity and restoring traditional landscapes (Wolpert et al., 2022).

3.2.3 Social options: behavioural changes

Science and technology are part of the solution but require a broad understanding and societal engagement to achieve transformation. The IPCC (2014) organises social options into (1) educational, including sharing local and traditional knowledge, participatory action research and social learning or knowledge-sharing and learning platforms; (2) informational, including climate services, integrating indigenous climate observations, community-based adaptation plans (or participatory scenario development); and (3) behavioural change (agroecology adoption would be included in this group). Behavioural change can facilitate deliberative transformation processes (Begum et al., 2022). Here we focus on behavioural change that affects the WEFE components.

In the food sector, policies and behaviour that operate across the food system, including those that reduce food loss and waste and overconsumption and that influence dietary choices, enable more sustainable land-use management, enhanced food security, zero waste, clean water and other benefits. The Mediterranean diet (*Figure 3.4*) has recently received increased attention due to its potential to reduce human pressure on the environment (Dernini et al., 2017). It is widely acclaimed for its health and sustainability benefits and is suited to the agroecological conditions of Mediterranean climate areas, as both the diet and the agroecosystems have evolved jointly over millennia (Aboussaleh et al., 2017). The beneficial role of the Mediterranean diet in sustainable development, based on a greater consumption of vegetables, fruit and fish, involves striking a balance between food production, and protection of ecosystems, biodiversity and agricultural practices (Burlingame & Dernini, 2011). Returning to locally-based production systems with reduced resource use, together with a reduction in super-intensive livestock production, could increase food security in the Mediterranean region (Dernini et al., 2017). Recovering certain agricultural practices from traditional Mediterranean landscapes (such as multi cropping, terraces, etc.) would be more labour-intensive. Doing so might only be possible through public policies to subsidise this kind of production.

However, adherence to this diet by the population of Mediterranean countries has progressively decreased (Obeid et al., 2022; Vilarnau et al., 2019). Meat overconsumption has been associated with current dietary patterns in the Mediterranean, and is an important factor for GHG emissions, associated with changes in land use, industrial processes, transport and energy (see *Chapter 2*) (Castaldi et al., 2022). Recovering the Mediterranean diet, particularly in European countries, has been shown to be linked to benefits across the WEFE nexus (Germani et al., 2014), including reduced water footprint (Blas et al., 2019; Vanham et al., 2021), reduced energy use and overall biocapacity use (Bôto et al., 2022; Galli et al., 2017), a more healthy diet (Guasch-Ferré & Willett, 2021; Sofi et al., 2014; Tilman & Clark, 2014), improved ecosystems through reduced eutrophication potential, land use and GHG emissions (Belgacem et al., 2021; Berry, 2019; Bôto et al., 2022; Dernini et al., 2017) while promoting biodiversity use, conservation and sustainable natural resources management (Aboussaleh et al., 2020; Capone et al., 2012). According to Sanz-Cobena et al. (2017), a 40% reduction in meat and dairy consumption could reduce GHG emissions by 20–30% in the Mediterranean. In Spain, following Spanish dietary recommendations could reduce GHG emissions by 17% (42% when considering diets' nutritional qualities) (Batlle-Bayer et al., 2019), while increasing adherence to the Mediterranean diet would reduce GHG emissions (72%), land use (58%) and energy consumption (52%), and to a lesser extent water consumption (33%) (Sáez-Almendros et al., 2013). Cutting down consumption waste could further decrease diet-associated GHG emissions by 10% (Batlle-Bayer et al., 2019). Also, in Spain, a comparison between the

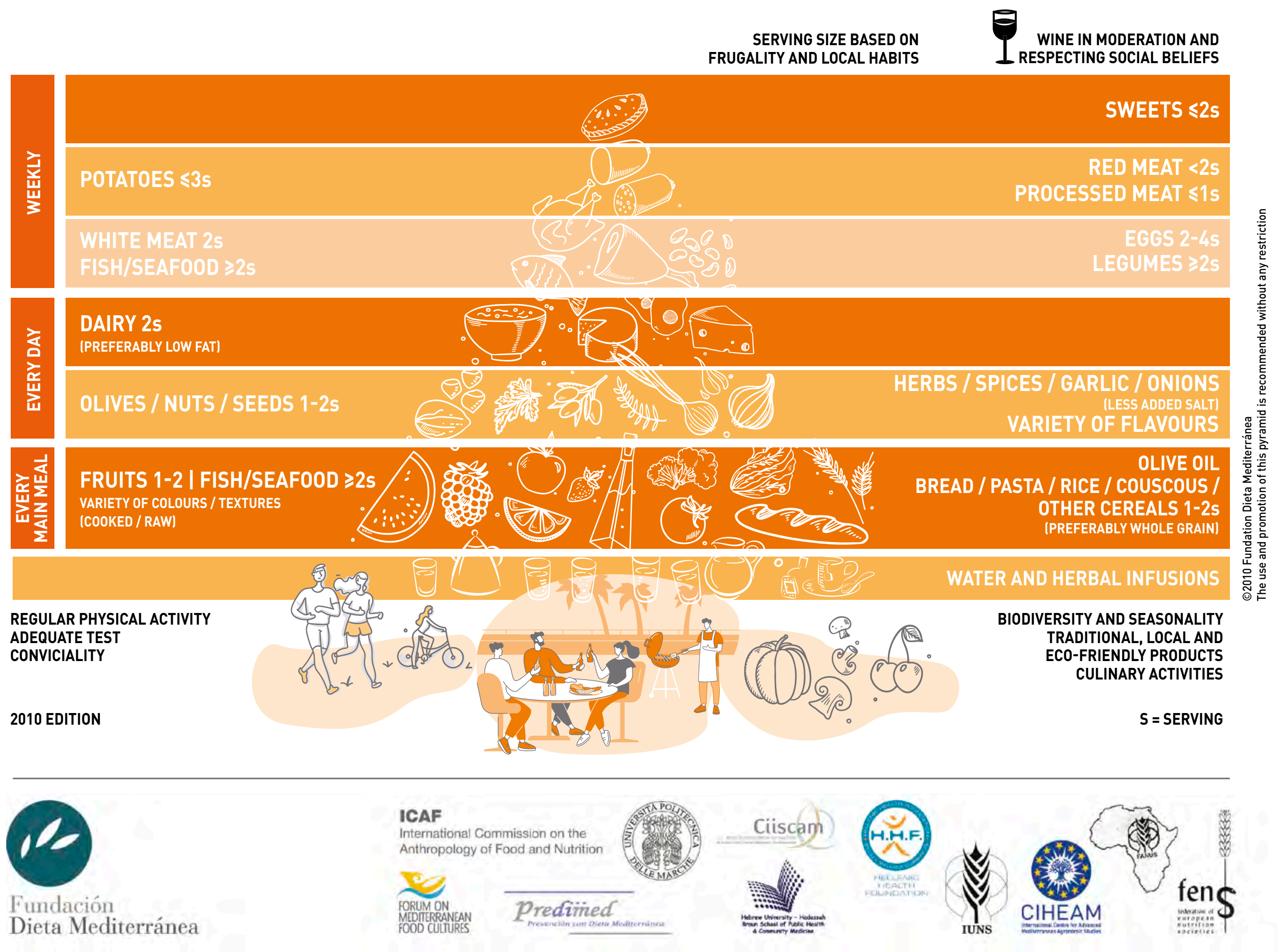

Figure 3.4 | The Mediterranean diet pyramid.
Source: Bach–Faig et al. (2011).

EAT-Lancet diet and Spanish current dietary patterns shows that the EAT-Lancet diet requires less water resources (3056 l day^{-1} per person) and a lower level of GHG emissions (2.13 kg CO_2 eq day^{-1} per person) than the Spanish diet (3732 l day^{-1} per person and 3.62 kg CO_2 eq day^{-1} per person, respectively) (Cambeses-Franco et al., 2022). In the MENA region, changes towards healthy diets, in four food groups (red meat, vegetables/beans, nuts/seeds, and fruit), can result in a median reduction in total water footprint of approximately 20% and a reduction in GHG of approximately 45%, but a median increase in blue water footprint of approximately 27% and an increase in energy use of approximately 56% (Bahn et al., 2019). Analysis conducted in different regions of Türkiye revealed that adherence to the Mediterranean diet resulted in lower GHG emissions (Bayram & Ozturkcan, 2023). The ability of production systems to sustain the Mediterranean diet also requires local animal breeds and plant species enhancing agrobiodiversity and the capacity of farmers to adapt to climate change (Bach-Faig et al., 2011). To account for these benefits, a new Mediterranean diet pyramid has been developed that includes both the health and environmental dimension (Bach-Faig et al., 2011; Serra-Majem et al., 2020) (*Figure 3.4*) as well as new indicators to measure the multifunctionality of the Mediterranean diet (Prosperi, 2015).

Despite existing differences between northern, southern and eastern Mediterranean countries in terms of contribution to environmental degradation, statistics show a rapid growth in resource consumption trends in MENA countries (e.g. electricity consumption may triple by 2025) and in pollution. Pollution risks are expected to increase in these countries, which calls for smart developments integrating green and circular a

WEFE nexus adaptation and mitigation strategies	Existing management responses in the Mediterranean basin	Water pillar SDG 6		Energy pillar SDG 7		Food pillar SDG 2		Ecosystem pillar SDG 14 SDG 15	
Governance and Institutional	Policies on water pricing and limiting and reducing water use (3)	++	o	++	o	++	o	++	o
Technological options	Use of renewable energy in agricultural and other sectors (42)	+++	o	+++	-	+	-	+	-
	Early warning systems and climate services (7)	+++	o	+	o	+++	o	+	o
	Digitalisation and precision agriculture (2)	+++	-	+	o	++	o	+	o
	Increased bio-energy crop production in marginal areas (8)	++	-	+++	o	+	o	++	-
Water conservation and irrigation solutions	Unconventional water resources and improved use efficiency (12)	++	-	+	-	+	-	+	-
	New irrigation techniques (16)	++	--	+	--	+	o	+	o
	Water reuse for irrigation (11)	+++	o	+	-	++	-	+	o
Nature- and ecosystem- based approaches	Nature based solutions (10)	+++	-	+++	o	+	o	++	o
	Agroecological management practices (18)	+++	o	+++	o	+++	-	++	o
Social options: behavioural change	Mediterranean diet and restrained consumption (30)	+++	o	++	o	+++	o	+++	o

IMPACTS AND RISKS

- + Positive impacts on WEFE nexus pillars
- - Risk or trade–off on WEFE nexus pillars
- Limited
- Medium
- Robust

LEVEL OF AGREEMENT/CONFIDENCE

- +++ High
- ++ Medium
- + Low
- o Low agreement or limited evidence

b

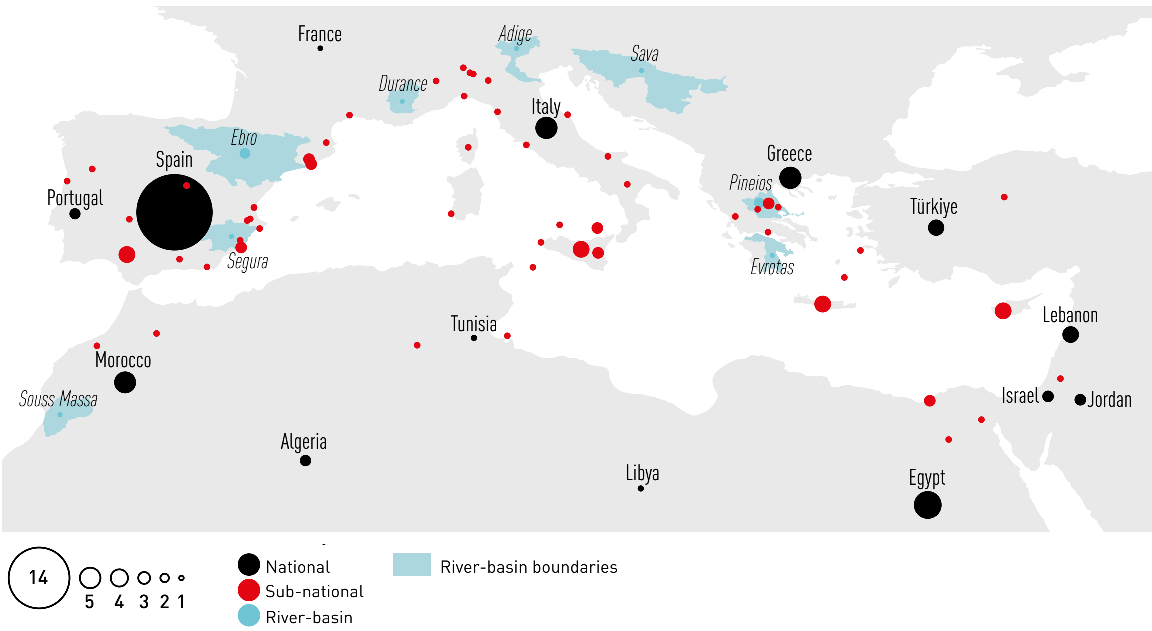

Figure 3.5 | (a) Assessment of the main impacts and trade–offs of the WEFE nexus adaptation and mitigation solutions implemented in the Mediterranean countries. The link is made to the SDGs through the nexus pillars. The numbers in brackets are the number of articles used for assessing each solution. The amount of evidence is quantified by the number of reviewed articles (given by numbers in brackets and categorised by limited in red, medium in orange and robust in green), while the degree of agreement measures the consensus between the articles (o for low agreement or limited evidence, + for low level of agreement/evidence, ++ for medium and +++ for high). This table does not review all possible solutions, but those implemented in the Mediterranean, reported in the scientific literature and assessed in the report. **(b) Spatial distribution of examined case studies.**

economy approaches, given the projected strong industrial growth linked to population growth and lifestyle changes (de Villamore-Martín, 2016). A paradigm shift in the way in which goods and services are consumed and produced around the Mediterranean is also proposed to decouple development from environmental degradation and resource depletion. A nexus approach may help foster an efficient use of energy and water in the food production process while reducing food waste and negative externalities (Kibler et al., 2018; Laso et al., 2018). The current food production system is to a large extent part of the growth-based economic system and is overall very productive but extremely inefficient in terms of energy use, also leading to ecosystem degradation. The Spanish agrifood system uses 6 units of energy to produce one unit of energy available in the form of food (Infante Amate & González De Molina, 2013). Transforming agrifood systems for sustainability means moving beyond the growth paradigm. It requires reconceptualising human food metabolisms according to values, food practices and lifestyles that strive for sufficiency, regeneration, distribution, commons and care (McGreevy et al., 2022), focused on needs and rights (Koch et al., 2017). A move towards agroecology and corresponding new consumption patterns (i.e. local, seasonal food, less meat consumption) can reduce resource use in the agrifood system and contribute to degrowth (Infante Amate & González De Molina, 2013) and the principles above, providing multiple benefits across the WEFE. Aguilera and Rivera Ferre (2022) estimated a net carbon sequestration of 24 Mt CO_2 eq yr^{-1} for an agroecological transition in Spain that combines the Mediterranean diet and reduction of food loss and waste with changes in agricultural practices. Compared to the present situation, this transition would free 8.2 Mh in third countries, reduce water contamination from nitrates by 87% and the consumption of fossil fuels for the supply of domestic food consumption by 84%, bringing it entirely within the limits of the country's natural resources. Reducing food loss and waste, which have increased with the industrialisation of agriculture, and promoting circularity within food systems, can also have a series of positive interactions with other WEFE components (Edwards & Nelson, 2020). Food loss and waste impacts include waste of the resources that are used to produce and process the food (e.g. land and water, see Blas et al., 2016, 2018), GHG emissions, land degradation, and ground and surface water pollution caused by the intensive use of nitrogenous fertilisers in agriculture, together with the impacts of agriculture expanding into wild areas and mono-cropping biodiversity loss (Lacirignola et al., 2014; Mbow et al., 2019). In this shift, small-scale farms are considered the main sustainability actor, providing higher yields and biodiversity in their farms (Ricciardi et al., 2021).

An assessment of the main impacts and trade-offs of WEFE nexus adaptation and mitigation solutions is summarised in *Figure 3.5*.

3.3 Challenges of WEFE interventions for mitigation and adaptation

3.3.1 Financial challenges and multiple societal and environmental goals

Assigning monetary values to solutions that span different aspects of the WEFE nexus remains difficult (Gambella et al., 2021). Financing such approaches can be further hindered by the fact that WEFE programmes have many important socially-oriented components that are typically of limited commercial value and potential (Adamovic et al., 2019). Nevertheless, by addressing different societal and environmental goals at the same time, WEFE approaches are the optimal for achieving several sustainability agendas (see *Chapter 5*).

First, they could help achieve many of the targets set by the United Nations Sustainability Development Goals (SDGs; see *Chapter 4*). In particular, the WEFE nexus directly targets SDG 2 "Zero hunger", SDG 6 "Clean water and sanitation", SDG 7 "Affordable and clean energy", SDG 11 "Sustainable cities and communities", SDG 12 "Responsible consumption and production", SDG 13 "Climate action", SDG 14 "Life below water", and SDG 15 "Life on land" (UN, 2015). Secondly, the WEFE nexus could offer a suitable platform for fulfilling existing agricultural policies, such as the European Union Common Agricultural Policy (CAP). The CAP has several clear sustainability goals that will lead to a more sustainable agricultural system for the EU, and where a nexus approach is necessary: climate change action, environmental care, and preserving landscapes and biodiversity (European Commission, 2019).

Overall, large amounts of funding could be required, which will require the adoption of fiscal and funding policies (Gambella et al., 2021), as well as changes to subsidies (FAO, 2022) to support behavioural changes. This is why the awareness-raising and education of policymakers, and the general public is a prerequisite (as mentioned in the previous section). WEFE approaches can become viable through Public-Privates Partnership (Adamovic et al., 2019). While public funding might be necessary initially, it should at some point be blended with private contributions.

3.3.2 Scientific challenges

The WEFE nexus is a relatively new concept and one of the major issues is the lack of available data and indicators to enable a science-based assessment of its impacts. One of the main advantages of WEFE approaches is the many benefits they can offer different sectors (Carvalho et al., 2022). At the same time, this advantage makes it very difficult to assess these benefits. This inherent complexity and the multi-disciplinary nature of nexus mean the models and methods to assess them and provide results of the full spectrum of their benefits need to cover many different scientific fields. In addition, the data are not necessarily collected or available over the long-term, meaning that in many cases, original data is necessary to showcase the benefits of WEFE approaches compared to other solutions. One approach to address this could be open data platforms with successful examples and the benefits of their implementation. Ideally a bottom-up approach that takes into account the different sub-models would be used to quantify the nexus. A Nexus Project Toolkit based on experience from real-life examples of nexus projects can increase wider acceptance of the nexus approach (Adamovic et al., 2019). This would also facilitate the cross-sectoral coordination at the relevant levels of governance that is a necessity for this approach to be truly successful and effective. The ecosystem services community has a lot of experience in mainstreaming novel data and modelling approaches, and moreover, integrating them into relatively simple and straightforward frameworks, which the WEFE nexus could build upon (e.g. Natural Capital Project, 2023).

To accurately assess the impact of WEFE approaches, they need to be implemented at different scales (Carvalho et al., 2022). Currently many efforts have been implemented at a micro-scale in urban settings primarily focusing on neighbourhood scale and rarely at the city scale. Future research efforts need to focus on moving on towards the meso- and macro-scale.

3.3.3 Urban challenges

Natural resources in the Mediterranean are seriously limited, and this can lead to conflicts between different sectors. Increasing urbanisation is both a Mediterranean and global trend that will continue to increase with many negative environmental impacts (Almenar et al., 2021; Keivani, 2009). WEFE approaches can therefore be used to help develop sustainable and healthy urban environments. The key for their successful implementation will be to address the needs of the people of the urban area, requiring knowledge about the causal relationships between water and ecosystem services, energy and food needs and urban challenges. Other essential components, that in many cases are neglected in the design of WEFE approaches, are the social, cultural and economic parameters. In most cases, this will be the key factor for long-term adoption and maintenance. One of the major sectors that urban areas are competing with for resources is agriculture. In the Mediterranean, irrigated agriculture provides the major livelihood income for rural areas but is also the largest consumer of freshwater, the most limited resource in the region (Daccache et al., 2014). In the future, demands for domestic and industrial water use, as well as water for energy generation, is expected to increase, leading to potentially increasing conflicts between urban and agricultural water users (Flörke et al., 2018). This means that both reduction in water use by households, tourism, industry and agriculture, as well as efficiency improvements in the Mediterranean will be necessary, while ensuring sufficient water for ecological functioning. The WEFE nexus can be of use when navigating through different users, limiting and reducing potential conflicts.

3.3.4 Geographic challenges

The Mediterranean has numerous coastal and mountainous areas with a high diversity of use intensity, topographic characteristics and population density. Mediterranean coastal areas are heavily urbanised, which will likely increase in the future (Reimann et al., 2018). Mediterranean mountainous areas, however, are facing a demographic decrease and/or abandonment (Bruno et al., 2021). This divergence between urban and rural areas, but also between intensively managed landscapes and semi-natural vegetation in the hinterland means that different WEFE aspects could be important across the Mediterranean region. Whereas in the coastal areas, WEFE approaches can alleviate the problems caused by increasing population and tourism, in the mountainous regions WEFE approaches could help better manage abandoned areas that used to be productive, but will also provide an incentive to maintain the young generation or attract people that prefer to live in less stressful conditions closer to nature. Moreover, different countries in the region will have different levels of acceptability and adoption of WEFE approaches. Many northern Mediterranean countries (e.g. France, Italy, Spain) that have strong economic, governance and social adaptation readiness are more likely and more financially ready to support such initiatives (Sarkodie & Strezov, 2019). In contrast, the southern and eastern countries of the Mediterranean could require international support and commitment in the form of financial or scientific support to increase the adoption of the new approaches that will lead to the sustainability of the entire Mediterranean in the long term. This difference is primarily between the northern and southern-eastern Mediterranean countries and should be considered when developing WEFE approaches. Moreover, some studies underline that northern countries rely on a large net appropriation of resources from the Global South (Hickel et al., 2022), and this is also true for Mediterranean countries. This can be exacerbated by international crises, which are detrimental to international changes. In this sense, resilience to the impacts of changes and related expected crises would also greatly benefit from relocating water, energy and basic food production as much as possible within every country.

3.3.5 Knowledge integration challenges

Missing expert and traditional knowledge and data on the interconnections between water, energy, food and ecosystems is a disadvantage for supporting integrative and diverse discussions on the application of the WEFE nexus. In the Mediterranean region, systemic approaches to increase resilience include agroecology (transhumance, pasture and forage management, agroforestry and fire management through grazing) as well as water catchment techniques for proper management of ecosystems (e.g. Aguilera et al., 2020; Oteros-Rozas et al., 2013). For example, the majority of the ancient Mediterranean grape and olive growing sites follow the layout of the terracing and the water systems network that allows for water storage, energy saving and food production, also contributing to shaping the landscape (Laureano, 2007). These traditional practices offer valuable insights in creating holistic and sustainable approaches, which inherently consider the WEFE nexus, while enabling the recovery of traditional knowledge and the coproduction of new local knowledge for enhancing resilience. Although traditional knowledge may be replaced or its practice hindered as sophisticated technologies provide ways of saving time and effort, when these technological means become more expensive or inaccessible, the return to traditional practices emerges as an adaptation strategy to global change in the Mediterranean, again reinforcing traditional knowledge (Ponti et al., 2016). Integration of different types of knowledge thus remains a feasible objective to develop WEFE-based strategies and support North-South collaboration.

Box 3.4

Case study: transboundary basins, the Sava River Basin

The Sava Basin is in the Western Balkans, spanning Bosnia and Herzegovina, Croatia, Montenegro, Serbia, Slovenia, and Albania (*Figure 3.6*). Substantial proportions of residents of these countries live in the Basin. The Basin is of high importance to these populations since it provides freshwater, hydropower, and hosts considerable portions of the Western Balkan's economic activity. Stakeholders from the different sectors, ministries and various interest groups relevant to the nexus participated in a workshop organised by the United Nations Economic Commission for Europe (UNECE, 2016). A key output of the workshop was identifying the current conditions and related trade-offs regarding nexus linkages (*Figure 3.7*).

The solutions identified to address the intersectoral challenges in the Sava River Basin are (UNECE, 2016):

- **Institutional solutions:** Improving existing governance by clarifying roles and responsibilities in order to monitor

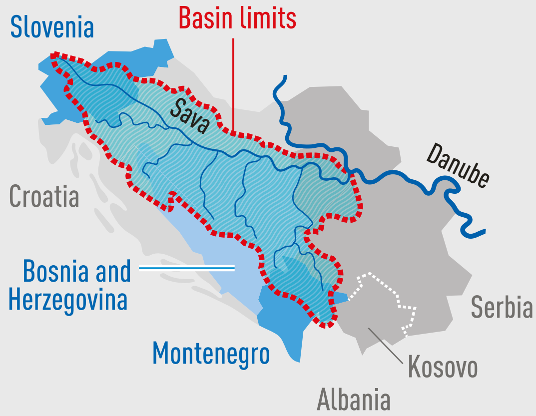

Figure 3.6 | The Sava River Basin.
Source: UNECE (2016).

the resources of the basin and support implementation of sustainable development principles.

- **Knowledge sharing / Data sharing solutions:** Develop a shared knowledge base. This should include monitoring, forecasting and guidelines on best practice for harmonising approaches (e.g. navigation, hydropower or ecotourism), as well as policy instruments aimed at resource efficiency (e.g. adoption of low-flow appliances in households, water and energy efficient technologies, and efficient irrigation practices).
- **Infrastructure solutions:** Flexible use of infrastructure (e.g. dams, irrigation and drainage systems), upgrading water infrastructure (e.g. wastewater treatment); investments in renewable energy sources (e.g. hydropower); and protection of natural infrastructure (e.g. floodplains and riparian areas and wetlands).

The international stakeholders identified numerous nexus benefits from the improved management of basin resources (UNECE, 2016). Identified economic benefits included: viability of economic activities, development of the agricultural sector, development of sustainable river tourism, reduced economic costs of water-related hazards, reduction of transport costs or increased volume of traffic, lower energy costs and reduction of water infrastructure costs. Social and environmental benefits included employment opportunities (e.g. agriculture and tourism), reduced human casualties of water-related hazards, health benefits from improved water quality, improved water services for users, and improved recreational opportunities. In addition, there are numerous potential indirect nexus benefits from enhanced trust between the countries of the Sava Basin, such as: increased trade through waterways, development of regional markets for goods, services and labour, and increased cross-border investments.

One prerequisite for successful nexus implementation is international coordination and cooperation at basin and regional level. This was achieved by utilising a pre-existing legal and institutional framework for cooperation at international and inter-sectoral scales. Specifically, the International Sava River Basin Commission (ISRBC) enabled the establishment of joint objectives that can be implemented by different countries at different stages of development. Different interest groups (recreation and tourism, industry, agriculture or navigation) are represented to discuss, coordinate and develop intersectoral plans and the establishment of integrated systems. To further enhance the ISRBC, an agreement on the implementation of the Framework Agreement on the Sava River Basin (FASRB) and its protocols, the EU Water and Flood Directives, as well as transboundary planning processes such as the Sava River Basin Management Plan and the Flood Risk Management Plan for the Sava River Basin were signed.

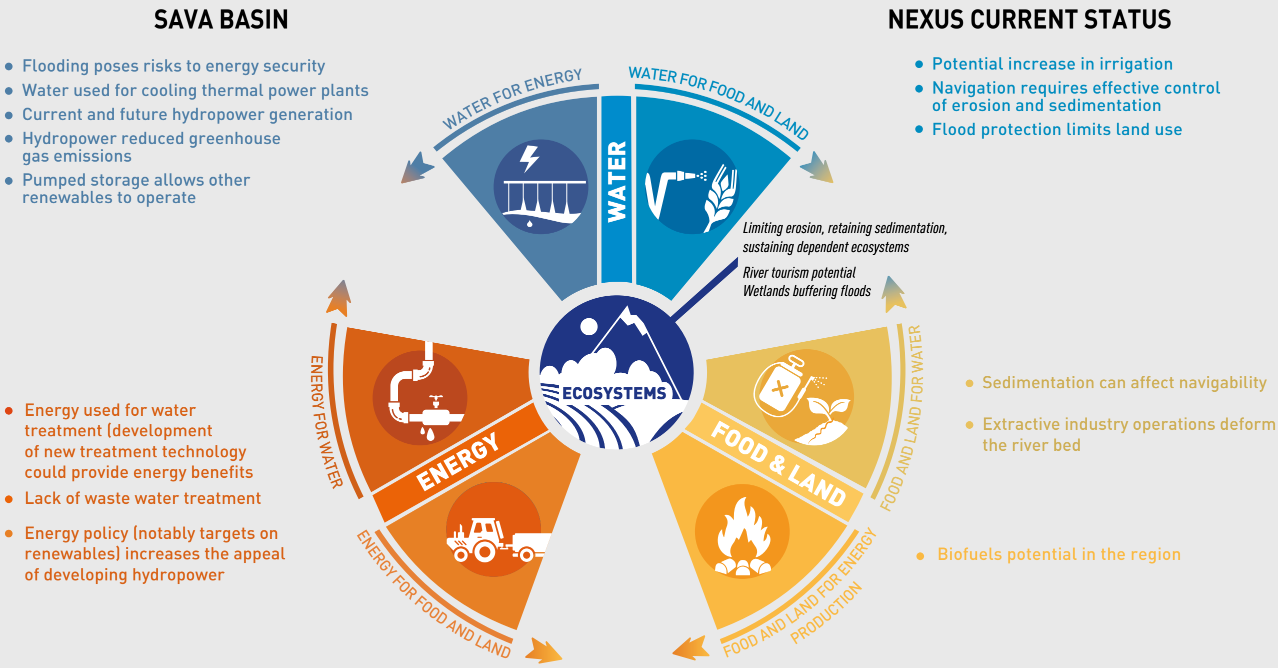

Figure 3.7 | The current status of the WEFE nexus linkages in the Sava River Basin.
Source: UNECE (2016).

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Contributions of the WEFE nexus to sustainability

4

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Chapter 4
Contributions of the WEFE nexus to sustainability

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Executive summary

The Mediterranean region is grappling with significant challenges involving water insecurity (e.g. water stress), energy insecurity (e.g. electrification level), food insecurity (e.g. undernourishment and malnutrition), and ecosystem insecurity (e.g. biodiversity loss, deforestation and pollution). These challenges, amplified by climate change, have profound implications for sustainable development in the region, evidenced by the fact that most countries have yet to achieve, or are not progressing towards achieving the SDGs relating to food security (SDG 2 – zero hunger), water security (SDG 6 – clean water and sanitation), energy (SDG 7 – affordable and clean energy), and ecosystems, both marine ecosystems (SDG 14 – life below water) and terrestrial ecosystems (SDG 15 – life on land).

Traditionally, the approaches and efforts to address sustainability challenges in the Mediterranean WEFE sectors have been supply-oriented, sector-focused, and fragmented, often failing to adequately consider the intricate interconnections between different resource systems. However, scholars and policymakers in the Mediterranean are increasingly acknowledging the need for systematic and integrated governance approaches and innovative tools to account for interdependencies between sustainability challenges and approach them holistically to address sustainable development challenges in the Mediterranean region. This need has prompted the emergence of integrated approaches for analysing and managing the interactions between components of the WEFE nexus and their trade-offs and synergies. The WEFE nexus has therefore evolved to focus on achieving SDGs by improving water, energy and food security, as well as the functionality of ecosystems through increasing the efficiency of resource use, reducing trade-offs, strengthening synergies, and enhancing governance across different sectors. However, existing research efforts and policy initiatives on the WEFE nexus in Mediterranean countries have tended to be conceptual, reaffirming the importance of the concept, but there is still a lack of concrete examples of the actual implementation of such an approach. This limited effective implementation of WEFE nexus approaches in the region can be attributed to the fact that WEFE nexus approaches are data-driven and require widely accessible information and reliable data, which in many cases underpin the implementation of nexus approaches.

To transition from conceptualisation to implementation of the WEFE nexus approach, it is essential to develop appropriate methodologies and indicators for measuring, monitoring, and examining progress. The operationalisation of the WEFE nexus approach involves methodological challenges. First and foremost is that there is no single methodology best suited for all WEFE nexus challenges and at all scales, due to the diverse nature of the addressed problems, different resolutions and boundary conditions. Moreover, there is the need to better integrate both nature and societal domains. Holistic, predictive, transferable and scalable methodologies represent the general features most appropriate for operationalising the WEFE nexus approach. Finally, when operationalising the WEFE nexus approach, it is crucial to consider the existence of trade-offs (conflicting goals) and synergies (mutually beneficial outcomes) between sectoral sustainability policies across the SDGs. An awareness of the interconnection between goals is essential for making informed decisions. Without this awareness, trade-offs may arise, and progress towards one sustainability target could potentially hinder advancements towards other targets. Therefore, sustainability policies that effectively balance the preservation of ecological integrity and the promotion of economic growth and social equity often result in more instances of synergistic interactions between different SDGs. WEFE nexus interventions that holistically address both ecological and socioeconomic concerns tend to yield positive outcomes across multiple goals.

4.1 The looming resource challenge and the Sustainable Development Goals in the Mediterranean region

Land and water ecosystems, and the biodiversity they support, provide essential resources for the Mediterranean's livelihood and human settlements. However, as shown in *Chapter 2*, population growth, agricultural intensification, urbanisation, and industrial production, together with the impacts of climate change, are creating competition for these resources, leading to rapid degradation. More than seven years after the adoption of the 2030 Agenda and its 17 SDGs, Mediterranean countries still face major sustainability challenges including water security, poverty, hunger, malnutrition, widening socioeconomic inequality, energy insecurity, pollution, and environmental degradation. To tackle these challenges, it is essential that policymakers aim to enhance the resilience of WEFE systems.

For the WEFE water component, the scarcity of water resources stands as a crucial challenge for sustainable development in the Mediterranean region, exerting considerable pressure on available water resources (*Table 4.1*). In addition, the region is grappling with the dual challenges of water-resource mismanagement, and an uneven distribution, exemplified by the fact that 90% of the 1140 billion m³ yr⁻¹ blue water ends up in the northern countries, leaving a mere 10% for the southern countries (Benoit & Comeau, 2006; Burak & Margat, 2016; Fader et al., 2020; OECD, 2012). Moreover, the transboundary nature of numerous river basins in the region along with the mounting uncertainties associated with climate change contribute to the complexity of addressing water scarcity challenges (IPCC, 2022).

Despite the endowment of Mediterranean countries in terms of hydrocarbons, the region still faces some challenges in securing its energy supply and matching demand. While access to electricity is universal in northern Mediterranean countries, this is not the case in many countries in other parts of the region (World Bank, 2022). However, in general, Mediterranean countries are still highly dependent on fossil fuels to produce electricity. Renewable energy consumption only comprises 11% of the total energy consumption in the region, which is less than the world average (OME, 2020). CO_2 emissions have doubled from 1971 in the Mediterranean, with France, Italy, and Spain generating almost half of them. Energy insecurity in the region is also driven by political conflicts between countries (Bartoletto, 2020) (*Table 4.1*).

Food insecurity, undernourishment and malnutrition are pressing issues in the Mediterranean too, especially in southern and eastern countries (FAO, 2022c). However, it should be highlighted that the food insecurity in the region is characterised by the triple burden of malnutrition (*Table 4.1*). That is, malnutrition is not only about food shortages, but also about poor and unbalanced diets, as over 20% of the adult population in almost all Mediterranean countries is obese (FAO, 2022c). The prevalence of overweight children is a matter of great concern, especially in southern and eastern regions (UNICEF et al., 2023). The Mediterranean region is also characterised by large disparities between sub-regions, with a significant gap between the northern and southern and eastern regions. Population growth and certain levels of political conflict in some areas have been identified as being behind food insecurity and malnutrition in the region (Abis, 2018; Abu Hatab & Hess, 2021; The Economist Intelligence Unit, 2016).

As for the WEFE ecosystem component, the Mediterranean region is considered a world biodiversity hotspot, in which biodiversity loss is taking place at a much more rapid pace than in other regions (IUCN, 2018, 2022). Biodiversity loss, deforestation, and land use changes, as well as pollution, are widely reported trends that are severely undermining Mediterranean ecosystems (*Table 4.2*). Overall, in the last few years, forests are slightly expanding in the basin. However, forest degradation is expanding too (Peñuelas & Sardans, 2021). The region is still subject to diverse forms of pollution, while some polluting sectors are undergoing rapid growth, such as coastal mass tourism or transport (UNEP/MAP and Plan Bleu, 2020).

According to the 2020 SDG dashboard, a global assessment tool for measuring countries' progress towards achieving the SDGs, the Mediterranean region has an overall SDG Index score of 73.5 but there are huge differences between the sub-regions (Riccaboni et al., 2020). The SDG index shows better performance in western Europe and lower values in eastern Europe, North Africa and the Middle East (*Table 4.3*). The SDG scores of Mediterranean countries range from 81.1 in France (ranked 4th globally) to 59.3 in Syria (global rank: 126). In particular, Mediterranean countries have not yet achieved the SDGs relating to food (SDG 2 – zero hunger), water (SDG 6 – clean water and sanitation), energy (SDG 7 – affordable and clean energy), and ecosystems, both marine ecosystems (SDG 14 – life below water) and terrestrial ecosystems (SDG 15 – life on land). Moreover, for most of these SDGs, moderate, significant and, even major challenges remain. In particular, the progress towards achieving SDG 2 presents a great concern, where none of the Mediterranean countries had achieved the SDG by 2020, and either significant or major challenges remain. The situation is worst among North African countries, where all countries face major challenges with achieving the SDG targets. The situation appears slightly better for water and energy. With water (SDG 6), only Libya faces major challenges (*Table 4.3*). For most Mediterranean countries,

Country	Water			Energy			Food		
	Freshwater withdrawal as % of total renewable water resources *2019*	Water stress (%) *2019*	Agricultural water withdrawal as % of total renewable water resources *2019*	Access to electricity (% of the population) *2020*	Access to electricity, rural (% of rural population) *2020*	Electricity production from oil, gas and coal sources (% of total) *2015*	Prevalence of undernourishment (% population) *2019–2021*	Prevalence of moderate or severe food insecurity (% population) *2019–21*	Prevalence of obesity in the adult population (% 18 years and older) *2016*
Albania	3.74	6.79	2.29	100.0	100.0	0.0	3.9	30.9	21.7
Algeria	84.01	137.92	57.17	99.8	99.6	99.7	< 2.5	19.0	27.4
Bosnia and Herzegovina	0.81	2.02	N/A	100.0	100.0	64.5	< 2.5	12.6	17.9
Croatia	0.63	1.48	0.075	100.0	100.0	33.2	< 2.5	11.4	24.4
Cyprus	25.89	27.61	21.28	100.0	100.0	91.2	< 2.5	N/A	21.8
Egypt	134.78	141.16	106.69	100.0	100.0	91.7	5.1	27.3	32.0
France	12.72	23.50	1.41	100.0	100.0	6.1	< 2.5	5.9	21.6
Greece	14.78	20.46	11.85	100.0	100.0	71.1	< 2.5	6.8	24.9
Israel	65.39	100.42	66.91	100.0	100.0	97.7	< 2.5	14.2	26.1
Italy	17.79	29.99	8.88	100.0	100.0	60.2	< 2.5	6.3	19.9
Jordan	100.51	104.31	60.89	99.9	98.8	99.0	16.9	43.0	35.5
Lebanon	40.23	58.79	15.54	100.0	100.0	97.4	10.9	29.1	32.0
Libya	817.14	817.14	692.85	69.7	7.8	100.0	N/A	39.4	32.5
Malta	81.18	81.18	45.54	100.0	100.0	92.3	< 2.5	5.2	28.9
Montenegro	N/A	N/A	N/A	100.0	100.0	50.3	< 2.5	14.0	23.3
Morocco	36.45	50.75	31.57	100.0	100.0	81.5	5.6	31.6	26.1
North Macedonia	16.31	25.26	5.14	100.0	100.0	64.1	3.3	20.9	22.4
Palestine	39.37	47.01	22.77	100.0	100.0	N/A	N/A	28.7	N/A
Portugal	7.91	12.31	4.41	100.0	100.0	51.9	< 2.5	11.6	20.8
Slovenia	2.96	6.38	0.009	100.0	100.0	32.4	< 2.5	7.4	20.2
Spain	26.42	40.17	17.26	100.0	100.0	44.1	< 2.5	8.6	23.8
Syria	83.11	124.36	87.31	89.1	75.6	97.7	N/A	N/A	27.8
Tunisia	81.92	95.99	63.54	100.0	100.0	96.1	3.1	28.0	26.9
Türkiye	29.08	45.70	25.647	100.0	100.0	67.8	< 2.5	N/A	32.1
Source	*FAO (2022a)*			*World Bank (2022)*			*FAO et al. (2022)*		

Table 4.1 | Water, energy, and food insecurities in the Mediterranean region.

reaching SDG 7 (affordable and clean energy) is still a challenge despite variable progress over time in some of them. Both marine and terrestrial ecosystems face significant challenges in the Mediterranean, where most countries are not on track to achieve SDGs 14 and 15. With SDG 14, twelve Mediterranean countries (Albania, Algeria, Italy, Lebanon, Libya, Malta, Montenegro, Morocco, Portugal, Slovenia, Syria, Türkiye) still face major challenges, while seven others (Cyprus, Egypt, France, Greece, Israel, Spain, Tunisia) face significant challenges. The situation is a bit better regarding terrestrial ecosystems (SDG 15), but 10 Mediterranean countries (Algeria, France, Greece, Italy, Lebanon, Libya, Montenegro, Portugal, Spain, Tunisia) nevertheless face significant challenges, whereas Jordan, Syria, and Türkiye have to address major challenges to achieve it. Of particular interest and requiring further monitoring is the fact that the SDG score decreased in most of the Mediterranean between 2020 and 2022, probably because of the impacts of the COVID-19 pandemic and its management (Bayoumi et al., 2022; Lafortune et al., 2022).

Country	Forests and deforestation			Biodiversity loss		Pollution
	Forest land 2000 (1000 ha)	Forest land 2020 (1000 ha)	Forest land change 2000–2020 (%)	Number of threatened coastal taxa *	Number of threatened marine taxa **	Plastic waste littered in the coastal belt (tonnes/day)
Albania	769.3	788.9	2.5	16	49	3.5
Algeria	1579	1949	23.4	36	55	47.5
Bosnia and Herzegovina	2111.65	2187.91	3.6	18	34	1.7
Croatia	1885	1939.11	2.9	27	56	8
Cyprus	171.61	172.53	0.5	15	40	4.2
Egypt	59.21	44.98	−24.0	24	44	77.2
France	15288	17253	12.9	62	63	66
Greece	3600.23	3901.8	8.4	39	64	39
Israel	153	140	−8.5	29	42	39.5
Italy	8369.25	9566.13	14.3	49	68	89.8
Jordan	97.5	97.5	0	-	-	-
Lebanon	138.18	143.33	3.7	20	37	7.3
Libya	217	217	0	14	43	11.6
Malta	0.35	0.46	31.4	16	37	1.7
Montenegro	827 (2010)	827	0	24	47	0.7
Morocco	5506.54	5742.49	4.28	48	56	25
North Macedonia	957.55	1001.49	4.59	-	-	-
Palestine	9.08	10.14	11.7	16	15	3.8
Portugal	3281	3312	0.9	-	-	-
Slovenia	1233	1237.83	0.4	18	43	1.0
Spain	17093.93	18572.17	8.6	63	72	125.6
Syria	432.08	522.08	20.8	24	38	12.9
Tunisia	667.85	702.73	5.2	26	54	20.9
Türkiye	20148.35	22220.36	10.3	34	53	144
Source	*FAO (2022b)*			*IUCN (2018), UNEP/MAP and Plan Bleu (2020)*		*UNEP/MAP (2015)*

* *Includes amphibians; birds; reptiles; mammals; freshwater fish; freshwater molluscs; freshwater crabs, shrimps, and crayfish; butterflies; dung beetles; saproxylic organisms and plants.*
** *Includes anthozoans, marine fish (bony fish and cartilaginous fish), marine mammals and marine reptiles.*

Table 4.2 | Ecosystem insecurities in the Mediterranean area.

Country/ Subregion	SDG index score 2020	Global rank 2020	SDG 2 2020	SDG 6 2020	SDG 7 2020	SDG 14 2020	SDG 15 2020	SDG index score 2022	
France	81.1	4	🟠	🟡	🟡	🟠	🟠		73.1
Greece	74.3	43	🟠	🟡	🟠	🟠	🟠		65.7
Italy	77.0	30	🟠	🟡	🟡	🔴	🟠		70.6
Malta	76.0	32	🔴	🟠	🟢	🔴	🟡		64.9
Portugal	77.6	25	🔴	🟡	🟢	🔴	🟠		70.6
Spain	78.1	22	🔴	🟡	🟡	🟠	🟠		70.1
Europe West	78.5	18							
Albania	70.8	68	🔴	🟠	🟡	🔴	🟡		-
Bosnia and Herzegovina	73.5	50	🟠	🟠	🟠	⚪	🟡		-
Croatia	78.4	19	🟠	🟢	🟡	🟡	🟡		70.7
Cyprus	75.2	34	🟠	🟡	🟡	🟠	🟡		60.7
Montenegro	70.2	72	🔴	🟠	🟡	🔴	🟠		-
North Macedonia	71.4	62	🟠	🟠	🟠	⚪	🟡		62.9
Slovenia	79.8	12	🔴	🟡	🟡	🔴	🟡		74.0
Europe East	74.8	38							
Israel	74.6	40	🔴	🟠	🟠	🟠	🟠	-	
Jordan	68.1	89	🟠	🟠	🟡	⚪	🔴	67.4	
Lebanon	66.7	95	🔴	🟠	🟡	🔴	🟠	63.6	
Palestine	-	-	⚪	⚪	⚪	⚪	⚪	-	
Syria	50.3	126	🔴	🟠	🟠	🔴	🔴	50.8	
Türkiye	70.3	70	🔴	🟠	🟠	🔴	🔴		56.7
Middle East (ME)	70.2	72							
Algeria	72.3	56	🔴	🟠	🟡	🔴	🟠	67.0	
Egypt	66.8	83	🔴	🟠	🟡	🟠	🟡	63.6	
Lybia	–	–	🔴	🔴	🟠	🔴	🟠	57.1	
Morocco	71.3	64	🔴	🟠	🟡	🔴	🟡	66.7	
Tunisia	71.4	63	🔴	🟠	🟡	🟠	🟠	67.3	
North Africa (NA)	70.2	72							
Mediterranean area	73.5	50							
Source	*Riccaboni et al.(2020)*							*Bayoumi et al. (2022)*	*Lafortune et al. (2022)*

🟢 *SDG Achievement* 🟡 *Challenges remain* 🟠 *Significant challenges* 🔴 *Major challenges* ⚪ *Unavalaible data*

SDG 2: *Zero hunger -* ***SDG 6:*** *Clean water and sanitation -* ***SDG 7:*** *Afordable and clean energy -* ***SDG 14:*** *Life below water -* ***SDG 15:*** *Life on land*

Table 4.3 | SDG scores in the Mediterranean region.

4.2 Nexus Solutions for Sustainable Development in the Mediterranean region

Traditionally, the approaches and efforts to address sustainability challenges in the Mediterranean water, energy, and food sectors, as well as ecosystems, have been supply-oriented and have often involved segmented planning and management frameworks (Malagó et al., 2021). In many cases, addressing one challenge has exacerbated others, underscoring the interconnected nature of these issues (Zarei, 2020). However, there has been increasing recognition among Mediterranean scholars and policymakers in recent years that achieving SDGs in the region requires systematic approaches and flexible forms of governance to account for interdependencies between sustainability challenges and approach them holistically (de Roo et al., 2021). Achieving SDG targets necessitates integrated approaches that offer innovative tools for tackling the complexities arising from multiple and often conflicting human needs. Such approaches should also foster an enabling environment for relevant stakeholders to collaborate effectively in managing the synergies and trade-offs between the food, water and energy sectors and their connections with the ecosystems (Magazzino & Cerulli, 2019).

The growing recognition of the need for such integrated approaches to address sustainable development challenges in the Mediterranean region has prompted the emergence of holistic approaches to analyse and manage the interactions between water, food, energy and ecosystems (WEFE). These approaches include, but are not limited to, soft path approaches for increasing water-use efficiency (Gleick, 2003), integrated water resource management (Biswas, 2008), integrated ecosystem management approaches (Botey & Garvin, 2010), multifunctional landscape approaches (Sayer et al., 2013), and more recently, nexus approaches (Bleischwitz et al., 2018; Weitz et al., 2014). Generally, these approaches are based on the underlying assumption that understanding the connections, synergies and trade-offs between WEFE components and sustainable development targets is crucial (Estoque, 2023; Hoff, 2011; Scott et al., 2015). The WEFE nexus has therefore evolved into an opportunity for achieving the SDGs by improving water, energy, food security and ecosystem functionality by increasing the efficiency of resource use, reducing trade-offs, strengthening synergies, and enhancing governance across different sectors (Malagó et al., 2021; Rasul, 2016).

Compared with most integrated approaches to sustainable development, nexus approaches offer comprehensive multi-sectoral frameworks for analysing the interactions between WEFE sectors, the identification of trade-offs and co-benefits that might otherwise be missed in complex production systems and supply chains and addressing institutional and policy implementation issues (Liu et al., 2018; van Zanten & van Tulder, 2021). Nexus approaches, such as the WEFE nexus, contribute to cross-sectoral cooperation and integrated planning and decision-making by accounting for the complex relationships between WEFE sectors and provide a framework for accounting for their driving forces which might be overlooked in single- or dual-sectoral approaches (Albrecht et al., 2018; Miralles-Wilhelm, 2016). In particular, the WEFE nexus approach has been largely embraced by Mediterranean stakeholders and decision makers due to its potential for improving governance across WEFE sectors by increasing efficiency, reducing trade-offs, and building synergies, which is particularly important in the context of Mediterranean countries where resource scarcity and sociodemographic pressures require efficient allocation, use and management of WEFE resources (Buchy et al., 2022; Endo et al., 2020). To ensure that the adoption of nexus approaches helps researchers and policymakers design and implement rigorous scientific assessments and effective policy interventions in relation to sustainable development objectives, key principles must be considered: (1) understanding the interlinkages between resources within a system across space and time and focus on the overall system's efficiency rather than the productivity of individual components; (2) offering integrated solutions, which contribute to achieving the sustainability goals and the security of water, energy and food resources; (3) accounting for the interdependence between water, energy, and food and promoting rational and inclusive dialogue and decision-making processes; (4) identifying integrated policy solutions to encourage mutually beneficial responses optimising trade-offs and maximising synergies across sectors; and (5) ensuring coordination across sectors and stakeholders for enhancing the potential for cooperation between all components (Carmona-Moreno et al., 2021).

Multiple frameworks and methodologies have been proposed to implement and operationalise the WEFE nexus approach (e.g. Afshar et al., 2022; Benson et al., 2015; Bizikova et al., 2013; Malagó et al., 2021; Mohtar & Daher, 2012), which put emphasis on multi-sectoral and non-linear system analysis and dynamic feedbacks across these sectors (Agrawal et al., 2022; Qin et al., 2022). Their applications reveal that renewable energies have a predominant role in achieving sustainability objectives in the Mediterranean region, especially SDGs 6.1 to 6.4 (clean water and sanitation) and 7.2, 7.3 (affordable and clean energy) that are strongly linked with 13.1 (climate action) (Malagó et al., 2021). The strongest interconnections between the SDGs and WEFE are for the categories of the renewable energy system, despite the tendency to focus on agriculture, so a more holistic nexus approach including end of supply chain options should be systematically integrated into the project design or evaluation. Trade-offs between agricultural production and environmental outcomes are intensifying, emphasising the importance of linking agricultural policies in the Mediterranean countries to environmental strategies and ecosystem protection programmes in order to resolve these trade-offs and ensure that food production goals are not achieved at the expense of ecosystems (Huang et al., 2023). More generally, applications of integrated assessment frameworks offer major policy implications for understanding the WEFE nexus in the region and the trade-offs between strategies to save water, reduce CO_2 emissions and/or intensify food production (Daccache et al., 2014).

As WEFE nexus frameworks continue to evolve, there have been some qualitative and less quantitative efforts in the Mediterranean region to explore whether the nexus approach, if properly designed and implemented, can effectively analyse the interconnections, identify synergies, and reveal trade-offs between WEFE sectors (e.g. Akinsete et al., 2022; Cristiano et al., 2021; de Roo et al., 2021). Nexus approaches proved the usefulness of assessing the impact of management strategies, policy interventions, and adaptation measures to climate-induced regional water constraints focusing on water availability, consumption and abstraction, and energy use (Espinosa-Tasón et al., 2020; Khan et al., 2016). In Spain, growing demand for irrigation water with limited supply has stimulated investments in water-saving and conservation technologies, with significant rebound effects (increased energy, irrigated area and water use), demonstrating the need for a change in the water policy paradigm from supply augmentation to demand management. At a larger scale, integrating the management of water and energy resources in Mediterranean countries is crucial to ensure the flexible operation of the energy system without affecting agriculture and water supply, and should include energy efficiency indicators and targets for the water sector (Adamovic et al., 2019). The WEFE nexus makes it possible to better identify potential synergies or conflicts between sector policies because it also provides a framework in which the role of ecosystem services is more explicit (Markantonis et al., 2019). Sustainable use of ecosystem services and conservation of biodiversity are indispensable pillars for successfully achieving sectoral development goals in the Mediterranean region.

An increasing number of regional organisations have launched or advanced regional programmes and initiatives to build mechanisms for supporting the WEFE nexus approach at various levels (Aboelnga et al., 2018), including the Association of Agricultural Research Institutions in the Near East & North Africa (AARINENA), the Center for Mediterranean Integration (CMI), the Global Water Partnership-Mediterranean (GWP-Med), the Union for the Mediterranean (UfM), the regional institutions of the League of the Arab States (LAS) such as the Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD), and the Arab Organization of Agricultural Development (AOAD). Involvement of stakeholders from the quadruple helix, (1) academia and education system, (2) economic system, (3) media-based and culture-based public (also civil society), (4) and the political system , in the development and implementation of nexus approaches is crucial to provide multiple perspectives, ensure political legitimacy and promote dialogue on the sustainability of WEFE components (Martinez et al., 2018).

A closer look at existing research undertakings and policy initiatives on the WEFE nexus in Mediterranean countries, however, reveals that most of these efforts have focused on assessments and analyses of the WEFE nexus, reaffirming the importance of the concept, but there is still a lack of concrete examples of actual implementation of the approach (Malagó et al., 2021). This limited effective implementation of WEFE nexus approaches in the region can be attributed to insufficient understanding of nexus trade-offs within science-policy-stakeholder interactions, insufficient incentives, limited vision, knowledge, development and investment, as well as the absence of strong empirical evidence of the potential benefits of a WEFE nexus approach (Hoff et al., 2019). Improving the gathering of data from different WEFE sectors is also a challenge to a better understanding and management of nexus interactions, and other interdependencies in the WEFE nexus, and a move from a general nexus thinking to an operational nexus concept (Laspidou et al., 2019). Indeed, WEFE nexus approaches are either data-driven or knowledge-based, and require widely accessible information and reliable data, which in many cases underpin the implementation of nexus approaches (Lawford, 2019; Simpson & Jewitt, 2019). The lack of complete and disaggregated data on the components of the WEFE nexus together with other issues related to data quality and accuracy, and unwillingness of authorities to make certain types of required data available to researchers and other stakeholders represent a major barrier to wider adoption and application of the WEFE nexus in the Mediterranean region (Markantonis et al., 2019; Robling et al., 2023). Another key challenge is related to the costs of nexus approaches which are generally higher than those of silo approaches, due to the information, expertise, time, coordination and financial resources required (Liu et al., 2018).

4.3 From concept to implementation: the need for appropriate methodologies and sustainability indicators for the WEFE nexus

Nexus indicators are valuable tools for understanding the complex interactions within the WEFE nexus and contributing to informed and effective decision-making. The nexus literature includes a broad range of methodologies from different disciplines and indicators that quantify the interdependencies between the nexus components (Albrecht et al., 2018; Arthur et al., 2019; Endo et al., 2020; Newell et al., 2019; Opejin et al., 2020; Robling et al., 2023; Zhang et al., 2018) (*Figure 4.1*).

Transdisciplinary methods are frequently combined with collection and analysis of data from institutions, agencies and governments, if available. Econometric techniques are one possibility for this sort of analysis, generally using regression relationships between nexus indicators to quantify the influence of one nexus component on another (e.g. Zaman et

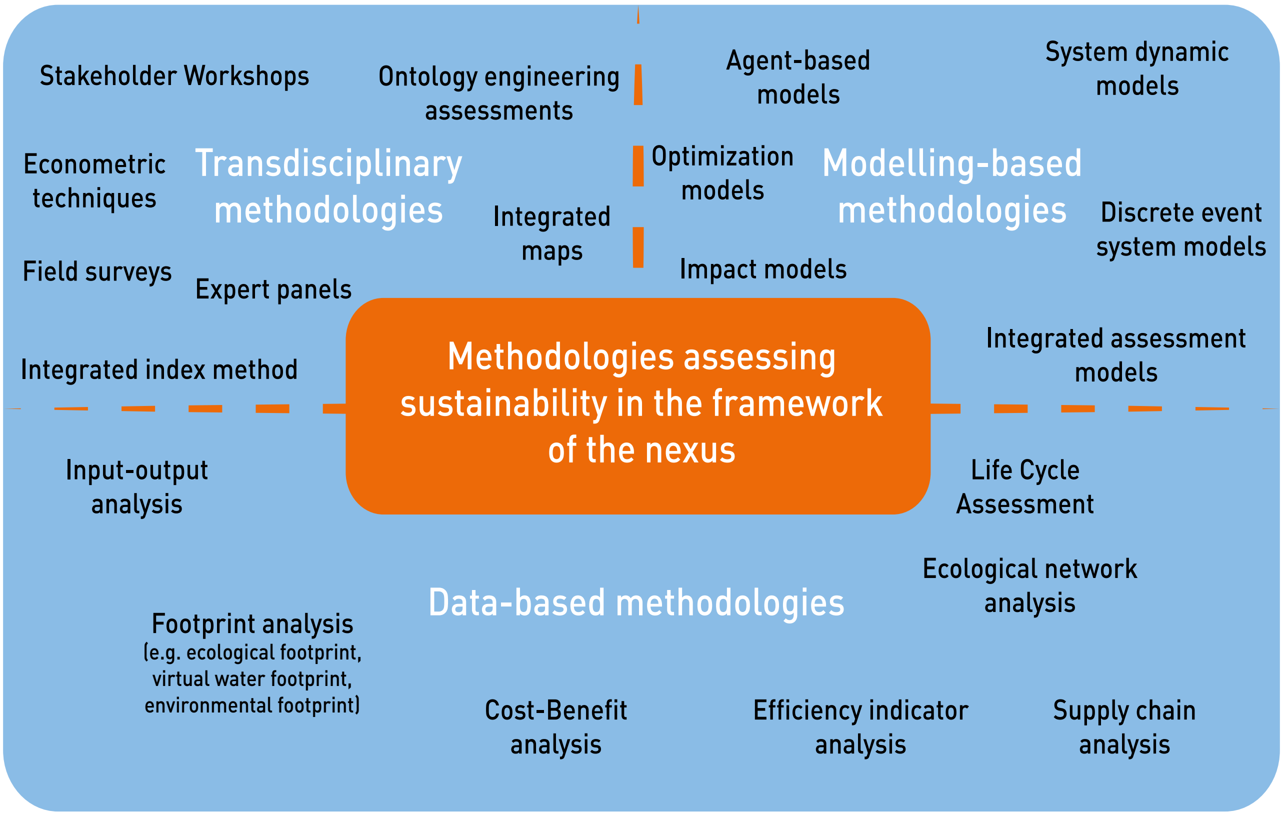

Figure 4.1 | Overview of the common methodologies used in the literature for sustainability analyses in the nexus.

al., 2016). The integrated index method is another possibility for capturing the characteristics of the nexus system by combining different indicators (e.g. de Vito et al., 2017; Endo et al., 2015; Schlör et al., 2018). Both options have the advantage of capturing current relationships observed in data but are rather static and not easily applicable for projections or predictions.

Field surveys, expert panels and stakeholder workshops are some of the most frequently used data gathering methodologies applicable for nexus assessments (e.g. Endo et al., 2015; Howarth & Monasterolo, 2016). They allow stakeholder dialogue and consider needs and views of interested groups. However, they are generally limited to the local scale and may be subject to bias originating from small or non-representative samples of participants.

In addition to transdisciplinary methods, a second group of methodologies can be identified as data-based approaches, including input-output analysis, material flow analysis, supply chain analysis, ecological network analysis, efficiency indicators, cost-benefit analysis (e.g. Endo et al., 2015), virtual water and water footprint studies (WF – e.g. Fader et al., 2011), environmental footprint (EF – e.g. Vanham et al., 2019) and life cycle assessments (LCA - e.g. Mannan et al., 2018). They focus primarily on measuring resource use, and in the case of LCA, the environmental impacts of production processes. These methods frequently compare and track outputs, inputs and production, in physical or monetary terms, making it possible to quantify performance and point out opportunities for efficiency increases. For more complete analyses within different sectors, the combined application of several indicators is recommended (Pacetti et al., 2015). However, these indicators are often applied to the present and past, since they rely mainly on measurement data, and lack projection power. For this reason, they are generally not suitable for the evaluation of future management practices or alternative scenarios.

In the modelling domain, a number of different modelling approaches have been applied to nexus research. For example, system dynamic models seek to demonstrate dependencies between variables (e.g. Sahin et al., 2014; Sušnik et al., 2018). Integrated assessment models are generally able to link interactions between nexus components and climate policies (e.g. the SEI nexus toolkit - Karlberg et al., 2015; MAgPIE and IMAGE Models - Doelman et al., 2022). Optimisation models, such as general and partial equilibrium models and land-use allocation models, seek to identify optimal solutions in interdependent systems with multiple possible solutions (e.g. MAgPIE and IMAGE Model – Doelman et al., 2022); GCE model - Teotónio et al., 2020). Impact models assess the consequences of actions in one system for other systems (e.g. Fader et al., 2013; CAPRI and E3ME - Trabucco et al., 2018), sometimes highlighting trade-offs and synergies (e.g. El-Gafy et al., 2017; Karabulut et al., 2019). Agent-based modelling simulates the behaviour of individuals or groups of individuals while allowing them to influence each other and learn from one another (e.g. Molajou et al., 2021). Each of these modelling frameworks has advantages and disadvantages described in the specific literature. Perhaps the largest advantage of models is the potential to run projections for the future and thereby help policy design and the avoidance of trade-offs before they happen. However, these methods require proper consideration of the linked parametric, input and model uncertainty encompassed in the results.

Finally, two methods are mostly used to visualise nexus relationships: (1) ontology engineering assesses terminology semantics on the internet and is a useful tool for depicting relationships between concepts (Endo et al., 2015); and (2) integrated maps depict the conditions of the nexus components at local level (Endo et al., 2015). They offer a useful tool for getting an overview of interdependencies and relationships.

4.3.1 Overview of applications of nexus indicators in the Mediterranean area

Several of the above-mentioned methodologies have been applied for nexus assessments in the Mediterranean region to estimate optimal cropping patterns that minimise water and energy consumption in Egypt (El-Gafy et al., 2017), assess benefits (Fader et al., 2016) or rebound effects neutralising water savings in irrigation modernisation projects in Egypt and Spain (El-Gafy, 2017; Mayor et al., 2015), or to evaluate energy strategy implementation (e.g. Karabulut et al., 2019). They show that increasing wind and solar energy in the Mediterranean as well as water use efficiency through modernisation of farms ranked high in terms of benefits for the water, food, ecosystem domain, benefits for socio-economic development, increase in resilience and green economy, and in the probability of implementation success (Karabulut et al., 2019). Linking renewable energy to desalinisation and wastewater treatment has positive effects on the environment, the economy and society, and brings benefits for the water, ecosystem, food and energy pillars (Lange, 2019; Malagó et al., 2021). Conversely, increasing bioenergy production, food production and promoting inland waterway transport are regarded as partially problematic or controversial for various nexus and sustainability areas (Karabulut et al., 2019; Pacetti et al., 2015). Energy for irrigation and the tourism sector may also strain the energy system if renewable energy does not replace energy production from fossil fuels (Sušnik et al., 2018). The example from Spain of combining stakeholder involvement, system dynamic modelling and ontology methods in a "serious games" framework has proved beneficial for estimating future irrigation water requirements (Sušnik et al., 2018), while in Cyprus, stakeholder dialogue has made it possible to analyse governance issues in nexus problems, compiling a list of practical innovations and their positive and negative impacts (Halbe et al., 2015).

The application of nexus methodologies briefly described above varies significantly in terms of (1) what sectors are considered, and (2) what temporal and spatial scales can be (and are in fact) covered. For example, nexus methodologies from the hydrological community are frequently applied and developed to assess problems at the watershed scale. In this case, nexus methodologies have much in common with Integrated Water Resources Management (IWRM) indicators (Kurian, 2017). Life cycle assessment (LCA) and footprinting are designed for past and present applications and can be applied to a variety of spatial scales or be focused on aggregation by products. LCA frequently accounts for the water and energy sector and some environmental issues. It is less often applied to the food sector. In general, it tends to be more applied to urban environments, highlighting the nature of cities as focused on consumption (e.g. Schlör et al., 2018; Yuan et al., 2021; Zhang et al., 2019).

Sustainability has economic, social and environmental components, but most nexus indicators combine only two of these areas. The social component, in particular, is frequently missing in most quantitative approaches. More emphasis on the combination of quantitative and qualitative analysis (Albrecht et al., 2018) as well as further development of agent-based models for nexus applications could partially close this gap in the years to come. However, developing new indicators involves the challenge of agreeing on which parameters to include as indicators due to the many different sectors involved in WEFE. Indicators that are too extensive or too complicated might be scientifically sound but not very applicable due to high data needs (Carvalho et al., 2022).

Indicators for local and regional scales and present and past times are widely applied to future projections and/or large scales (e.g. continental or global). Examples of these indicators include, for the nexus water component, total and per capita freshwater withdrawal, percentage of wastewater safely treated, proportion of population using safely managed drinking water services, agricultural water use efficiency, and level of agricultural, industrial and municipal water stress. Energy indicators include total primary energy consumption, percentage of investments in fixed assets in the energy sector in total volume of investments in fixed assets, total primary energy production, total primary energy consumption, oil production and consumption, electricity generation, gross electricity consumption, and biomass energy consumption. With regard to food, sustainability indicators include the food production index, fertiliser consumption, per-capita arable land, prevalence of undernourishment and food self-sufficiency ratio. For the ecological dimension of the nexus, indicators include ecological deficit, ecological footprint, biocapacity, CO_2 emissions per unit of GDP, forest area as a percentage of total land, urbanisation rate, and salinisation. Due to the limited capacity of some methodologies to assess future projection, as well as lack of data of sufficient quality, and since sustainability targets environmental, economic and societal well-being in the long term, not all nexus methodologies are able to contribute to sustainable development. Also, most nexus studies focus on the interactions between water, energy and food, with only a small number of them addressing nature or natural ecosystems as an additional "sector". There is therefore a clear need for increasing the role of holistic, predictive, transferable and upscalable methodologies for nexus research that include nature and environmental issues.

Nexus indicators are primarily a suitable tool for monitoring sustainability, but there is no perfect nexus methodology for all nexus questions and scales. There is a need for flexible indicators that make it possible to integrate additional components depending on case study, scale and question. One of the gaps in nexus synthesis research is the provision of decision support tools for stakeholders, managers and even researchers that offer an overview of which methodologies are best suited for which type of problems at different scales. Many measures are therefore still designed in "silos" (Lange, 2019; Malagó et al., 2021). Recommendations include taking a more holistic approach, considering complete supply chains, integrating modelling, and attempting more policymaking across national borders (Lange, 2019; Malagó et al., 2021; Saladini et al., 2018; Simpson et al., 2022). Strengthening governance, removing market distortions, promoting sustainable investments and raising awareness of the cross-sectoral consequences of policy design in the Mediterranean area are key to advancing water within the nexus approach while removing institutional, technical, regulatory and economic barriers (Kennou et al., 2018; Menichetti, 2018). New overarching policy approaches for management of energy, food and water resources are advocated to prevent potential trade-offs in climate change adaptation (Karabulut et al., 2018; Lakhdari, 2018).

4.4 Managing nexus synergies and trade-offs for sustainable resource use and management

Successful implementation of the WEFE nexus approach requires acknowledgement of the interdependence between water, energy, food, and ecosystems (Parsa et al., 2021; Robling et al., 2023). In order to adequately operationalise this approach, it is necessary to be aware of all trade-offs and synergies that might occur. To illustrate this, we take the example of the impact of sectoral sustainability policies on all SDGs, that is, beyond the SDGs these policies were designed for. To do so, representative sectoral sustainability policies designed to tackle sustainability in the different WEFE components' domains were identified from the literature. Then the impacts of each of these sectoral sustainability policies on the progress of all SDGs was estimated (*Table 4.4*). It should be underlined here that the criterion for selecting sectoral sustainability policies was neither exhaustivity, nor relevance, but representativity of the existing diversity of policies within each domain. The purpose of this qualitative analysis is to show that trade-offs and synergies are structurally present in the WEFE domain.

4.4.1 The WEFE ecosystems component

Five sectoral sustainability policies represent the existing diversity of policies within the Ecosystems component in the Mediterranean: (1) biodiversity and ecosystem conservation (CITES, 1983; RAMSAR, 2014); (2) action to minimise contamination and residues (UNEP, 2023); (3) sustainable intensification, that is saving land by separating production and preserved areas (FAO, 2011); (4) land sharing (European Commission, 2021), that is combining biodiversity preservation and agricultural production; and finally (5) payment for ecosystem services (e.g. REDD+). Biodiversity and ecosystem conservation policies tend to exert positive impacts on all SDGs except for those SDGs more linked to the promotion of economic activity (SDG 8), addressing climate change impact (SDG 13) and industry (SDG 9) or infrastructures (SDG 7, 11) where there can often be a clash of objectives. Action to minimise contamination and residue policies are largely in line with the previous groups of policies, and tend to show advantageous interactions with all SDGs, except for those more associated with the promotion of economic and industrial activity (SDGs 8, 9). The dual nature of sustainable intensification policies is largely reflected in the estimation of both detrimental and advantageous impacts on almost all SDGs. For land management, there is a longstanding tension between land sharing and sustainable intensification (e.g. Aubertin et al., 2022). This is clearly shown in *Table 4.4*, which displays the impacts of each of these sectoral sustainability policies on the progress of all SDGs. These two kinds of policies show radically opposed performance. Land sharing policies are largely aligned with biodiversity and conservation ones. Payment for ecosystem services policies perform quite ambivalently, with advantageous impacts on SDGs related to industrial, urban and economic activity (SDGs 8, 9, 11), and both detrimental and advantageous impacts coexisting in a good number of the remaining SDGs due to the money mediation inherent in this kind of policy, which frequently might not be the most effective way to minimise inequalities in multiple domains.

4.4.2 The WEFE water component

Six sectoral sustainability policies offer a good picture of the existing diversity of policies within the water component: (1) cooperation in the protection and use of transboundary water resources (UNECE, 2013); (2) conservation of aquatic ecosystems and wetlands (RAMSAR, 2014; WHO, 1999); (3) promotion of water efficiency (FAO, 2022c; Salman et al., 2019); (4) water footprint reduction (FAO, 2022c); (5) promotion of adequate water sanitation to protect human health and the environment (WHO, 1999); and finally (6) large water infrastructure development (e.g. groundwater wells, dams, aqueducts, storage tanks) to secure drinking water, hydroelectricity generation and/or irrigation (2030 WRG, 2022). As shown in *Table 4.4*, cooperation in the protection and use of transboundary water resources policies show advantageous impacts in the progress of all affected SDGs. The conservation of aquatic ecosystems, as might be expected, shows the same performance as biodiversity and ecosystem conservation and is also largely aligned with land sharing policies, with generally advantageous impacts except for SDGs 7, 8, 9 and 11. Promotion of water efficiency and water footprint reduction policies are two types of highly related policies that impact the same SDGs. However, while the former attempts to improve water use without questioning the number of utilisations, the latter implies a change in water consumption patterns. This explains the existing differences in the SDGs related to economic growth and industry (SDGs 8, 9), as well as those related to equity (SDGs 1, 2, 6, 10, 12), and to natural resource conservation (SDGs 14, 15). Water sanitation policies are estimated to exert advantageous effects on all SDGs impacted. Finally, large water infrastructure development policies (e.g. groundwater wells, dams, aqueducts, storage tanks), are characterised by exerting a dual impact on most of the SDGs, except for SDGs 8, 9 and 11, which are focused on urbanisation and economic and industrial development.

4.4.3 The WEFE food component

Four sectoral sustainability policies, according to the specialised literature, depict the existing diversity within the food component: (1) food security (CFS, 2020; FAO, 2022c); (2) food safety (WHO, 2022); (3) equity in nutrition (Development Initiatives, 2020); and finally (4) agroecology for food security (FAO, 2018). Food security policies aim to guarantee basic needs by reducing hunger, poverty, and enhancing well-being (SDGs 1, 2, 3). However, they have ambiguous impacts on SDGs that incorporate equity issues, due to the multiple options for enhancing food production and distribution (SDGs 4, 5, 6, 8, 9, 10, 11, 16). Food safety policies aim to ensure safe and healthy food consumption to minimise foodborne diseases. These policies are largely in line with food security policies. However, they show more ambivalent performance in guaranteeing access to food (SDGs 1, 2). Implementation of these policies tends to be associated with positive interactions with economic growth, industrialisation, urbanisation and responsible consumption (SDGs 8, 9, 11, 12). The emphasis of agroecology on enhancing equity and environmental awareness in the promotion of sustainable food systems means that implementation of agroecological policies is associated with advantageous interactions with almost all SDGs. The only negative interactions identified are with economic growth, industrialisation, and urbanisation (SDGs 8, 9, 11). Equity in nutrition policies aim to guarantee access to nutritious and culturally appropriate food for all people, but less focus on environmental issues explains the more ambiguous performance of these policies in SDGs 13, 14 and 15.

4.4.4 The WEFE energy component

The following group of sectoral sustainability policies provide a fair overview of the existing diversity of policies within the energy component: (1) decarbonisation (European Commission, 2021; IEA, 2021); (2) energy efficiency (European Commission, 2019); and (3) renewable energies (IRENA, 2014; REN21, 2014; SDSN, 2019). As shown in *Table 4.4*, decarbonisation policies show advantageous interaction with all SDGs as a consequence of the environmental awareness they are based on, but also because of their focus on reducing fossil fuel dependence, with multiple implications in terms of equity enhancement. Trade-offs seem to take place with SDGs 8 and 9, as decarbonisation is not well aligned with economic growth and industrialisation. And it also shows some negative interactions with urbanisation (SDG 11). Largely in line with decarbonisation policies, the adoption of policies to support renewable energy tends to entail synergistic interactions with most SDGs. However, trade-offs can be identified with

Sectoral sustainability policies		Relationship to SDGs																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Ecosystem	Biodiversity and Ecosystem Conservation *(CITES, 1983; RAMSAR, 2014)*	+	+	+	+	+	+	*	-	-	+	*	+	+	+	+	+	+
	Preventing contamination *(UNEP, 2023)*	+	+	+	+	+	+	+	*	-	+	+	+	+	+	+	+	+
	Sustainable intensification *(FAO, 2011)*	*	*	*		*	*		+	+	*	+	*	*	*	*		
	Land sharing *(European Commission, 2021)*	+	+	+		+	+		-	-	+	-	+	+	+	+		
	Payment for ecosystem services *(e.g. REDD +)*	*	*	*		*	*		+	+	-	+	*	+	*	*		+
Water	Cooperation in transboundary waters *(UNECE, 2013)*	+	+				+	+	+	+	+				+		+	+
	Conservation of aquatic ecosystems *(RAMSAR, 2014; WHO, 1999)*	+	+	+	+	+	+	*	-	-	+	*	+	+	+	+	+	+
	Water efficiency *(FAO, 2022c; Salman et al., 2019)*	*	*				*		+	+	*	+	*	+	*	*		
	Water footprint reduction *(FAO, 2022c)*	+	+				+		-	-	+	+	+	+	+	+		
	Water sanitation *(WHO, 1999)*	+	+	+	+	+	+		+	+	+	+	+		+	+	+	
	Water infrastructure development *(2030 WRG, 2022)*	*	*	*		*	*	*	+	+	*	+	*	*	*	-		
Food	Food security *(CFS, 2020; FAO et al., 2022)*	+	+	+	*	*	*		*	*	+	*					+	
	Food safety *(WHO, 2022)*	*	+	+	*	*	*		+	+	*	+	+					
	Equity in nutrition *(Development Initiative, 2020)*	+	+	+	+	+	+		*	*	+	+	+	*	*	*	+	
	Agroecology for food security *(FAO, 2018)*	+	+	+	+	+	+		*	-	+	*	+	+	+	+	+	+
Energy	Decarbonisation *(European Commission, 2021; IEA, 2021)*	+	+	+	+	+	+	+	-	-	+	*	+	+	+	+	+	
	Energy efficiency *(European Commission, 2019)*	*	*	+	+	*	+	+	+	+	*	+	*	*	*	*	*	
	Renewable energies *(IRENA, 2014; REN21, 2014; SDSN, 2019)*	*	*	+	+	+	*	+	*	*	+	+	+	+	+	+	+	

Note: *+ means positive interaction; - means negative interaction; and * means both positive and negative interactions occur; empty cell means that data to show relevant interaction are not available.*

Table 4.4 | Qualitative examination of the synergies and trade–offs between the effects on the progress of SDGs arising from sectoral sustainability policies.

SDGs 1, 2, and 6. If an expansion of renewables leads to large-scale bioenergy production globally, then there is a risk of competition with land for food production (SDG 2) and water for multiple uses (SDG 6). Increased food prices could potentially result in such a scenario, which would be to the detriment of the poor worldwide (SDG 1). Also, the fact that renewable energies are still not always very competitive can generate trade-offs with certain objectives linked to economic growth and industrialisation (SDGs 8, 9). The potential rebound effect that might occur when efficiency is enhanced, together with the variable degree of equity regarding energy efficiency for all people, lie behind the potential trade-offs between several SDGs, particularly those more directly linked to ecological integrity (SDGs 12, 13, 14, 15) and equity (SDGs 1, 2, 5, 10, 16).

4.4.5 Synergies and trade-offs between the WEFE components

All the sectoral sustainability policies examined show multiple trade-offs and synergies when their impact is assessed for all SDGs (see *Table 4.4*). The examination also shows that this is independent of both the WEFE component the given policy was initially designed to tackle, and the nature of the policy orientation the given policy belongs to. The existence of trade-offs and synergies is the norm rather than the exception, that is, interdependence between WEFE components is a structural feature. Adequate operationalisation of the WEFE nexus approach needs to take this into account. In line with this, the examination also shows that sustainability policies with a focus on the preservation of both ecological integrity and social equity tend to perform in a more synergistic manner than those that do not. The existence of synergies and trade-offs between sectoral sustainability policies is not something specific to the Mediterranean region, as the diverse policies examined are present worldwide. However, it is also true that the Mediterranean is home to some specific features that put this region under even more pressure than others. The huge and multiple (cultural, socio-economic, orographic, bioclimatic, etc.) diversity within the Mediterranean, over a relatively small area of land and sea, makes this region particularly vulnerable to undesirable cross-effects between sectoral sustainability policies. Consensus around policy priorities might be more difficult to attain in such a heterogeneous region, where cross-effects between policies might be more abundant and less obvious. In this kind of context, integrated and holistic approaches to sustainability, such as the WEFE nexus approach, become more difficult to attain and therefore more necessary.

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Governance, policies and research options for the WEFE nexus

5

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Chapter 5
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Executive summary

There is an urgent need for coordinated WEFE policies in the Mediterranean to address water scarcity, food and energy insecurity, ecosystem health, and potential conflicts exacerbated by climate change. However, countries in the MENA region currently lack an integrated policy framework that connects water resources management, energy, food, and ecosystems. Given the profound impact of climate change on food and water security, implementing integrated, transformative, inclusive and WEFE-based policies in the MENA region is imperative in order to effectively manage water, energy, and food resources. Coordinated WEFE policies should take into account the intricate interconnections between biophysical and socio-economic systems. Transboundary considerations are also crucial, as policies in one country can affect WEFE security regionally and locally due to the inherent production and consumption linkages in global markets and trade. When designing WEFE nexus policies within the Mediterranean region, it is essential to account for their effects on other sectors, ecosystems, and countries through market interactions.

Governance for the WEFE nexus requires strengthened connections and better management through coordination, integration, coherence, and collaboration between actors and their respective strategies and actions, rather than through the creation of new institutions. In the Mediterranean Basin, especially in southern countries, there is insufficient cooperation between science and policy, with stakeholders often expressing different, and sometimes incompatible, goals, agendas, and priorities. Enhancing the science-policy interface in these countries presents an opportunity for integrated WEFE planning, management, and governance. It is imperative to avoid siloed approaches and instead focus on hybrid governance modes and policy instruments that are holistic and long-term. Citizens' assemblies based on deliberative processes can help overcome some limitations of current democratic systems and practices in responding to the climate crisis. WEFE challenges and interlinkages in the Mediterranean region can be more efficiently addressed by referring to frameworks such as social-ecological resilience, the Sustainable Development Goals (SDGs), or the 2050 Vision on Biodiversity.

Most projects funded under the Seventh Framework Programme for Research, such as ARIMNET and ERANETMED, have focused on technological and social innovations in the WEFE domains, and particularly water-ecosystem and energy-ecosystem links. Public-Private Partnerships have proven to be effective funding mechanisms for the WEFE nexus. Projects under Horizon 2020 and PRIMA programmes have significantly improved capacity-building and awareness among involved partners regarding WEFE components.

5.1 Overview of current policies

5.1.1 WEFE policy inventory

Numerous policy objectives have been formulated across the Mediterranean Basin, each linked to corresponding policy instruments, to achieve the policy goals set forth in the United Nations (UN) 2030 Agenda for Sustainable Development (UN, 2015c) and the UN Framework Convention on Climate Change (UNFCCC) (UN, 1992) – the two main policy documents related to the WEFE nexus at the international level (Munaretto & Witmer, 2017). Moreover, several other key policy documents are considered vital for resource efficiency, including the Convention on the Protection and Use of Transboundary Watercourses (UNECE, 1992) for water, the Paris Agreement for climate change and GHG mitigation (UN, 2015b), the Declaration of the World Summit on Food Security (FAO, 2009), the World Food Summit Plan of Action (FAO, 1996b), the International Treaty on Plant Genetic Resources for Food and Agriculture (FAO, 1996a), the OECD-FAO 2016 Guidance for responsible agricultural supply chains (OECD & FAO, 2016), the UN Convention to Combat Desertification (UN, 1994) (for managing land, food and ecosystems, and the Sendai Framework for Disaster Risk Reduction 2015 – 2030 (UN, 2015a). A pioneer of the WEFE concept at policy level is the Integrated Water Resources Management (IWRM) framework designed to improve water resources management adopted at the Dublin International Conference on Water and the Environment (ICWE) and the Rio de Janeiro Summit on Sustainable Development, both in 1992.

At the European level, WEFE-related policies are primarily focused on the just transition and sustainable development by fostering resilience in human and natural systems within the context of global environmental change. The European Green Deal (European Commission, 2021c) – the EU economic growth strategy, presented in December 2019, sets an ambitious and comprehensive roadmap for transforming Europe into the worlds' first climate-neutral continent by 2050, caring for nature, boosting the competitiveness of the European economy, improving people's health and quality of life, and leaving no one behind. From a WEFE perspective, the EU Green Deal includes some relevant strategies and legal initiatives, including: (1) the Farm to Fork Strategy (European Commission, 2020a), which aims to accelerate the transition to a food system, (2) the EU Biodiversity strategy for 2030 (European Commission, 2020b), which aims to protect nature and reverse the degradation of ecosystems, (3) the EU Soil Strategy for 2030 (European Commission, 2021a), which aims, among other things, to combat desertification and restore degraded land and soil, including land affected by desertification, drought and floods, and (4) the EU Adaptation strategy (European Commission, 2021b), which aims to reinforce the adaptive capacity of the EU and minimise vulnerability to the impacts of climate change.

This transformation involves a shift to a greener economic model, aimed at (1) net zero greenhouse gas emissions by 2050, (2) economic growth decoupled from resource use, and (3) inclusivity, so that no individuals or regions are left behind (Filipović et al., 2022). The "Fit for 55" initiative represents a coherent and balanced EU framework, designed to achieve climate goals by enhancing innovation and competitiveness across economic sectors, while ensuring equity and social justice for all citizens. The Kunming-Montreal Agreement (UNEP, 2022) adopted at the 15th Conference of the Parties (COP15) to the Convention on Biological Diversity (Canada, December 2022), outlines a key goal of restoring at least 30% of degraded terrestrial, inland water, coastal, and marine ecosystems by 2030. Accelerating the pace and scale of nature restoration is critical to improving lives and livelihoods, mitigating biodiversity loss, and countering climate change impacts, considering that 50% of global GDP depends on nature and 50% of crops are at risk of soil erosion.

In the Mediterranean region, climate and agricultural policies represent critical priorities, stimulating progress in and being positively influenced by energy, water, and ecosystem-related policies (Papadopoulou et al., 2020). Unlike EU countries, MENA countries lack a common policy framework. Policy directions for the Arab countries have been developed by the League of Arab States (LAS) and its relevant institutions. LAS is an intergovernmental organisation of all Arab states in the Middle East and North Africa. The Council of Arab Ministers Responsible for the Environment (CAMRE) was set up to maintain coordination and cooperation among Arab countries in areas related to the environment and climate change. The Arab Ministerial Water Council (AMWC) has the mandate to address increasing water scarcity in the region. In 2012, AMWC adopted the Arab Strategy for Water Security. The Arab Water Council is responsible for raising awareness of current water resources management challenges in the region. The Arab Organization for Agricultural Development (AOAD) is another specialised organisation under the umbrella of the LAS with the main mandate of coordinating agricultural-related activities for ensuring food security among the countries of the region. However, MENA countries maintain multiple bilateral and multilateral frameworks for managing water, energy, and food resources. The Gulf Cooperation Council (GCC) is one such platform that has developed a Unified Water Strategy spanning 20 years, from 2016 to 2035. Countries in the MENA region, such as Egypt and Libya, rank among the most water-scarce areas worldwide. Historically, their inhabitants have shown great wisdom in water usage, both in terms of developing water infrastructure and establishing governance mechanisms (de Stefano et al., 2014). A prime example is the traditional *qanat* system (equivalent to *foggara* and *falaj*), practised in this region, which effectively provided ownership of groundwater rights. However, two critical aspects of Integrated Water Resources Management – demand management and cost recovery – are urgently needed but have not been achieved in the MENA countries. Moreover, explicit reallocation of water from rural to urban users and from agriculture to industry has not been undertaken, and increasing supply has so far been the predominant focus (*Table 5.1*).

Implementing multiple policies simultaneously can either promote or obstruct progress towards objectives due to the interconnectedness of systems. Therefore, when deciding on policies to implement, potential cross-sectoral implications must be thoughtfully considered (Laspidou et al., 2020; Sušnik et al., 2021). Practical implementation of WEFE nexus policies has been limited and lacks coordination between the different levels of managing authorities, sectoral departments, political actors, and stakeholders (Bazzana et al., 2023; Ghodsvali et al., 2022). Different political and social conditions within Mediterranean countries imply varying levels of WEFE nexus policy implementation (*Figure 5.1*).

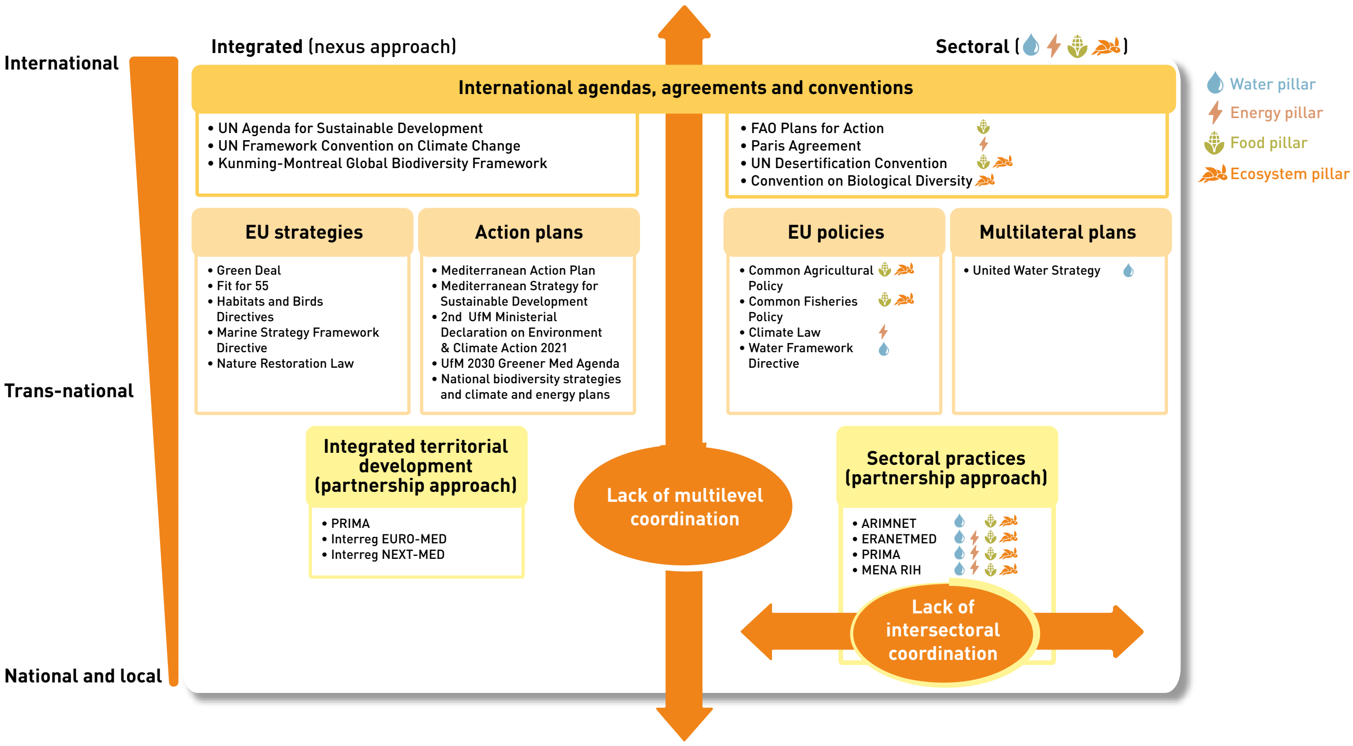


Figure 5.1 | Multi-level integrated and sectoral policies on the WEFE nexus in the Mediterranean (see *Sections 5.3.1* and *5.3.3* for AIMNET, ERANETMED, MENA RIH and PRIMA programmes description).

5.1.2 Lessons learnt at nexus policy level so far

The water, food, and energy nexus are coupled at multiple levels, which reveal institutional opportunities and obstacles to collaborative decision-making. While local challenges and pressures are important, the specificities from each territory make up-scaling into a broader perspective difficult (Scott et al., 2011). This is a complex issue with various alternatives, conflicting objectives, and multiple uncertainties about key drivers. This complexity requires the collaborative involvement of stakeholders to develop meaningful policy objectives (Ghodsvali et al., 2022).

In water-scarce regions, water and energy are not fairly priced or efficiently allocated, which means, from an economic perspective, that the societal impact of resource use is not optimised (Wichelns, 2017). The adoption of cooling technologies in these regions is critical for maintaining the balance between water-energy supply and demand (Qin et al., 2015). Smart water management, and the extensive use of technologies capturing Greenhouse Gases (GHGs) may ensure water security in water-scarce Mediterranean regions (Papadopoulou et al., 2022). The concept of virtual water and international trade of agricultural products may mitigate the impacts of water scarcity and improve food security in high-income countries, although globally it aggravates water scarcity in low and lower-middle income countries (Zhong et al., 2023).

Bridging sectoral policies to form interdisciplinary sustainable management strategies could contribute to a more balanced use of natural resources and conservation of natural capital. The sustainable use of ecosystem services, including ecosystem restoration and green infrastructure, are key elements for successfully achieving sectoral development goals (Karabulut et al., 2019). Policies related to the WEFE nexus in the Mediterranean Basin should aim to increase resource efficiency, balance demand and needs with a focus on sufficiency, and reduce waste and losses (Pistocchi et al., 2022). Given political instability and conflicts in the region, WEFE nexus governance should promote transparency, participation, deliberation and accountability through dialogue and cooperation between Mediterranean countries, supplemented by collaboration with international organisations, the private sector, civil society and citizen participation.

5.1.3 Gaps and synergies at legislative level in the context of WEFE diplomacy

Examination of the legislative landscape in the Mediterranean region for the WEFE nexus shows that a prominent deficiency is the absence of holistic integration across sectors (Cremades et al., 2021). Legislation and policies for water, energy, food, and ecosystems often exist as independent entities in several Mediterranean nations, leading to inefficiencies and conflicts between nexus components (Giest & Mukherjee, 2022). Furthermore, disjointed legal frameworks, marked by diverse and frequently conflicting laws, particularly in relation to transboundary resources, are particularly evident on both sides of the Mediterranean region. Even legislation that appears robust on paper can encounter implementation and enforcement hurdles due to institutional weaknesses, corruption, and limited resources. Lastly, current legislation does not sufficiently take into account the potential impacts of climate change, even though it is predicted to significantly influence the WEFE nexus in this region (see *Chapter 2*).

While these legislative gaps pose challenges, there are existing synergies that offer the potential for a more unified approach to managing the WEFE nexus in the Mediterranean, with the caveat that achieving policy coherence is not always possible and not necessarily optimal (Wichelns, 2017). These include platforms for regional cooperation, like the Union for the Mediterranean (UfM), which provides opportunities for legal harmonisation and collaborative resource management. Initiatives under the umbrella of UNESCO, such as the Intercontinental Biosphere Reserve of the Mediterranean, can also provide useful legislative (though non-binding) frameworks for encouraging movement towards a more holistic approach to territorial planning which takes the WEFE nexus into account. Mediterranean nations that are either EU member states or maintain strong ties with the EU could reap benefits by aligning their policies with the more advanced EU frameworks pertaining to water, energy, food, and ecosystems. The United Nations SDGs offer an extensive roadmap that can guide the formation of WEFE nexus legislation. There are several instances of successful integration in the region, such as IWRM, that could be used as a model for multi-sectoral legislative unification.

5.1.4 WEFE nexus – policy effects on multidimensional security through market interactions

Fostering the WEFE nexus in the Mediterranean region requires integrated policymaking that avoids resource inefficiencies. But to prevent trade-offs and maximise synergies between the different WEFE dimensions, policymakers should consider the economic interconnections between food, energy, and water systems when determining the impact of policy measures on food, energy, and water security. Generally, nexus policies are defined as interventions that directly affect at least one nexus component (Nielsen et al., 2015). Integrated nexus policymaking must account for the multidimensionality of security, which needs to be ensured both at macro level, i.e. national level availability of water, energy or food, and at micro level of the economy concerned with access to these resources at the household or individual level, often dependent on income and prices (Schuenemann, 2018) as well as societal norms and power inequalities. Both types of security are inherently interconnected, so nexus policies that directly affect only one nexus component can indirectly influence the entire WEFE nexus due to multiple connections between the nexus components (Nielsen et al., 2015) (see *Chapter 2*). It is beneficial to distinguish between biophysical linkages through ecological processes and social and economic interconnections. Economic interconnections arise from production and consumption linkages through market interactions between consumers and producers. Consumption linkages occur when consumers purchase goods and services at markets, such as food and energy. The prices and supply at these markets, that is access and availability, determine whether consumers can fulfil their demand. For example, a policy that increases energy prices could directly reduce energy security but also indirectly food security because it reduces the available income of households for consumption of other goods. Production linkages are input-output connections between different producers. This could be upstream linkages, where producers purchase intermediate inputs from other producers, or downstream linkages, where a producer sells its output to another producer (Diao & Thurlow, 2012). Continuing with the above example of a policy increasing energy production costs, current industrialised food production could be negatively affected by increasing input costs because there is an input-output connection between energy and food. As all economies in the Mediterranean region are open, producers and consumers can engage in international trade meaning that the supply and demand of trading partners can also influence the domestic WEFE nexus as well as WEFE in third countries through telecoupling (Garrett & Rueda, 2019; Liu et al., 2020). Türkiye, for example, is a major food hub for the MENA region (Schuenemann & Hess, 2023). If Turkish food production decreases or increases due to policy measures, it could affect exports and thus the availability of food in other countries within the MENA region if no internal measures are taken to enhance domestic production. In sum, market interactions lead to a multitude of linkages, so a policy measure invariably affects the rest of the economy and different parts of the WEFE nexus (Schuenemann, 2018). In the WEFE context, telecouplings between distal socio-ecological systems of production and consumption, as they become more visible, are giving rise to feedback mechanisms in the form of environmental and social governance (Garrett & Rueda, 2019).

Other policy options that can affect market interactions involve pricing. Water pricing aims to ensure that all water costs are accounted for, and encourages more efficient water use, thereby reducing impacts related to water use across the WEFE nexus (Cortignani et al., 2018). The European Water Directive encourages this, but other countries in the Mediterranean region have also started implementing it. Nevertheless, implementation of water pricing remains difficult, as in many parts of the region water use is subsidised, or prices have been frozen due to rising costs of other agricultural inputs (Molle & Sanchis-Ibor, 2019). Despite increases in water prices in many parts of the Mediterranean, full costs related to negative impacts of freshwater overuse and mismanagement are not covered or remain unaccounted for. In the food sector, correct pricing (including cost externalisation) is also being proposed to promote farming practices which are sustainable, and favour nexus approaches. The hidden costs of global food and land-based agricultural systems to the environment and public health have been estimated at around US$ 12 trillion per year and are expected to grow to US$ 16 trillion by 2050, mainly due to impacts on human health (including malnutrition) and pollution (FAO et al., 2021). This implies true price accounting to internalise the environmental, social and health costs of unsustainable farming practices and diets, including waste (Martin-Rios et al., 2023). This can take the form of taxes and financial mechanisms (e.g. taxes on sugar), but also repurposing current subsidies for the nexus so as to help reduce the price of sustainable and healthy food. The WEFE nexus therefore presents a suitable approach to start taking into account numerous impacts of water use on energy, food production and ecosystems.

5.1.5 From policy to action: levels and scales of WEFE nexus governance

Whether we are talking about extreme events, the frequency and intensity of which are on the increase (IPCC, 2021; Kron et al., 2019), or the continuing rise of temperatures, it is now recognised that the ability of governance systems to cope with uncertainty and surprise is an essential condition for their sustainability (La Jeunesse & Larrue, 2020). This is why Chaffin et al. (2014) propose defining adaptive governance and social learning as essential for governing socio-ecological systems during periods of abrupt change (Folke et al., 2005), such as ongoing climate change. However, knowledge of the relationship between the characteristics of governance regimes, the interactions between stakeholders, particularly water resource stakeholders, and their performance, is still fairly limited (Buchs et al., 2021; Pahl-Wostl, 2019), as is the ability to test them in the context of climate change (Sušnik et al., 2021). Moreover, the increase of water supply as an answer to increasing water demand is not being accompanied by the hoped-for radical changes in the dominant water consumption models for agriculture and tourism in the Mediterranean region (La Jeunesse et al., 2016).

In this chapter, WEFE nexus governance is not only the organisation of decision-making power at governance level, such as international (for transboundary basins), national, regional, and local levels, but also the ongoing decision-making processes that push (or block) for more cross-sectorality through interactions between stakeholders. Field studies have demonstrated two main facts (1) there are no universal solutions or plans for integrated resources management, and there are still wide-ranging debates about how to put the process into practice to make it effective (La Jeunesse & Quevauviller, 2016; Rogers & Hall, 2003); (2) capacity for action is found more in processes than in organisational structures. This concept, or method of application, is in line with the idea of self-organisation advocated by E. Ostrom[10], for whom different self-organising systems are supposed to be resilient and capable of coping with change, vulnerability and uncertainty (Ostrom, 2010). On the basis of this assumption, the state of WEFE nexus governance in a territory can be assessed by evaluating the quality of interactions between stakeholders that influence cross-sectoral decisions (Hüesker et al., 2022), as developed in the contextual interaction theory detailed below (Bressers et al., 2016).

Problem perceptions and environmental awareness

Everything confirms that the level of perception of the problem and environmental awareness is a key condition (Adger et al., 2009; Koop et al., 2017; La Jeunesse et al., 2016) for stakeholders to engage in decision-making processes (Bressers, 2009; Bressers & Kuks, 2004) encouraging more cross-sectorality to adapt to climate change (La Jeunesse & Larrue, 2020). Stakeholders are usually aware that there is a clear link between the level of environmental awareness and the level of environmental education of adults who are part of decision-making processes. In this regard, one recommendation is to invest in educational actions targeting adults involved in activities and decision-making processes for WEFE nexus components (La Jeunesse, 2020).

Lack of environmental expertise

A lack of environmental expertise in organisational structures impacts the capacity of governance to encourage more cross-sectorality. This can be associated with a low mobilisation of resources for the environmental sector and can occur at different levels in the decision-making process. When the lack is situated at the top level[11], it can block all the processes of designing national strategies and plans to support actions in territories. When it occurs at other levels, it can restrict the process of bottom-up initiatives and thus restrict implementation of actions. The mobilisation of environmental expertise and related resources can therefore increase the chance of being more effective (Bressers et al., 2016; Crona & Parker, 2012; OECD, 2018a).

Levels and scales of WEFE nexus governance

In multi-level systems, devolved governance should enable responsibilities to be allocated to the least centralised level, with potential for development at other levels (Lockwood, 2010). Moreover, governance is truly supportive of cross-sectorality when WEFE nexus governance issues can be addressed at different levels (upscaling and downscaling) and where WEFE domains work together in a coordinated manner (Bressers et al., 2016).

One of the difficulties faced by governments with the transformation processes required to respond to climate change by considering cross-sectorality is that they are looking for the effectiveness of a top-down framework which support bottom-up initiatives. While a climate-focused approach is considered to be top-down, since it starts with global projections of climate change and works down to the more local projections needed to analyse the local impacts on which adaptation policies are based, the bottom-up approach involves initiating reflection on the basis of local information regarding the possibilities for responding to the impact of climate change on resources (water, energy, food) (Bhave et al., 2014). This "bottom-up" approach is generally based on extensive consultation of the various local stakeholders and their networks who are involved in the decision-making process, including non-governmental organisations.

To conclude, the development of WEFE nexus governance in the Mediterranean region requires including all categories of stakeholders at different levels for top-down strategies and bottom-up initiatives to meet the same goals.

10 Elinor Ostrom, winner of the 2009 Nobel Prize in Economics, has developed analytical tools and identified the key factors for self-organisation in natural resource management. This has enabled her to develop hypotheses on the success of collective action. Her empirical approach is presented in her book "Governing the Commons: the Evolution of Institutions for Collective Action", first published in 1990. Prior to this theory of self-organisation, the theoretical models widely used to analyse the governance of "the commons" ultimately focused on government intervention and the market, which inevitably failed to manage public environmental resources because of the "tragedy of the commons" or the "crowding effect".

11 A top-down, vertical or hierarchical approach reflects a traditional conception of power. Orders emanate from above and are implemented at each level by a subordinate authority. Its classic graphic representation is the pyramidal organisation chart, with arrows going from top to bottom. In politics, the centralised State is an illustration of this. The criticisms levelled at this form of organisation are its rigidity, and its inability to take account of specificities and realities on the ground. The bottom-up or horizontal approach is a response to these criticisms: innovations and ideas emanate from "the bottom", i.e. from the local level, and are then passed on to the other hierarchical components of the entity in question so that they can be taken into account and implemented. Collaborative or participative approaches, federal or decentralised models are all part of this approach, which also aims to give responsibility to the lower level of the decision-making context.

Main WEFE policies in EU and non-EU countries of the Mediterranean region			
	EU	**Middle East**	**North Africa**
WATER	- Water Framework Directive. - Groundwater Directive. - Urban Waste Water Directive. - Circular Economy Action Plan *(substances released in water bodies)*. - Floods Directive. - Action Plan on the Sendai Framework for Disaster Risk Reduction (2016). - EU Parliament and Council decision on Union Civil Protection Mechanism.	- Mediterranean Action Plan (21 Mediterranean Countries and EU): aimed at protecting the Mediterranean Basin from pollution and promoting sustainable development. Includes a range of measures to improve water quality, prevent marine pollution, and promote sustainable use of coastal resources. - The Arab Strategy for Water Security (2013) and its Action Plan (2014) are based on the Integrated Water Resources Management (IWRM) principle. Priority objectives include strengthening adaptation to climate change. - Unified Water Strategy of the countries of the Gulf Cooperation Council (GCC). **CYPRUS** - The Water Development Department of Cyprus has developed a Water Policy for the Mediterranean Basin which includes several key components: Integrated Water Resources Management, water conservation, water quality, climate change adaptation, and international cooperation. In addition to the above-mentioned components, the water policy of Israel includes desalination and reuse. **LEBANON** - National Water Sector Strategy (NWSS) of Lebanon (2010): the key objectives are to increase water availability, improve water quality, ensure water distribution, and strengthen institutional capacity. **TÜRKIYE** - National Water Plan 2019–2023. - Water Efficiency Strategy Document and Action Plan 2023–2033 for Adaptation to Changing Climate Conditions.	National climate plans in North Africa concerning water resources: - Water saving, construction of dams and hill reservoirs, adaptation of technical itineraries, introduction of technical practices (direct sowing), reconversion of production systems, fight against erosion and desertification, anti-drought programmes, protection and rehabilitation of steppe lands, development of watersheds, rural projects, diversification of activities, safeguarding and extension of forests, development of agricultural insurance. - Strategies for responding to water-related disasters. - Water mobilisation (dams, desalination with cogeneration, underground injection, wastewater recycling, inter-regional transfers). - Water saving (supplementary irrigation, optimal techniques, leakage reduction, pricing, training and awareness). - Flood and drought control (vulnerability map, watershed management and reforestation, flood control, protection of urban areas, development of monitoring and information systems and decision-making tools). **ALGERIA** - Law no. 05–12 of 4 August 2005 on water. - National Water Plan 2035. **EGYPT** - National project to improve irrigation water management to reduce losses and waste (rehabilitation of the irrigation network by improving the condition of the irrigation canals) and the use of drainage water. - National plan for water desalination using solar energy. - Nexus of Water, Food and Energy (NWFE) programme. - National mega wastewater treatment projects. **MOROCCO** - The National Climate Change Plan in Morocco subsidises the construction of runoff storage basins to collect water from heavy rainfall. This programme focuses on conversion to localised irrigation. The Green Morocco Plan recommends developing arboriculture on dry land that is less sensitive to droughts. - National drinking water and irrigation water supply programme 2020–2027. - National Water Plan (PNE) 2020–2050. - National Plan for Flood Protection. - Green Generation Strategy 2020–2030. - National Programme for Mutual Sanitation, which aims at improving water quality by reducing pollution. **TUNISIA** - Sectoral water strategies. - Water Code of 1975. Several versions of the draft organic law on the Water Code have been prepared and submitted for consultation. Last version adopted in September 2019. - Water Sector Strategy 2030.

Main WEFE policies in EU and non-EU countries of the Mediterranean region			
	EU	**Middle East**	**North Africa**
ENERGY, Climate Change Mitigation	- European Green Deal: climate neutrality by 2050. - European Climate Law (Regulation (EU) 2021/1119). - EU Strategy on Adaptation to Climate Change (COM(2021) 0082). - Fit for 55 Package. - Integrated climate and energy policy for 2030. - Energy Union strategy (COM(2015)0080). - Governance of the Energy Union Regulation (EU) 2018/1999). - Risk-Preparedness Regulation (EU 2019/941). - Energy Efficiency Directive (2018/2002). - Energy Performance of Buildings Directive (EU 2018/844). - Renewable Energy Directive (EU 2018/2001). - EU Agency for the Cooperation of Energy Regulators (EU Regulation 2019/942). - Just Transition Fund (COM(2020)0022). - Bio-economy strategy.	- Mediterranean Strategy for Sustainable Development 2016–2025. - Union for the Mediterranean (UfM) Energy Ministerial Declaration (2017). - Mediterranean Energy Observatory. - Mediterranean Solar Plan (2008). - Euro-Mediterranean Energy Efficiency Forum. - Eastern Mediterranean Gas Forum. - MENA Renewable Energy Strategy (2020). **TÜRKIYE** - Türkiye National Energy Plan (2022). - Türkiye Hydrogen Technologies Strategy and Roadmap (2023). - 2024–2030 Climate Change Mitigation Strategy and Action Plan. - Environment Law No. 2872 (last amended by the Law No. 7456 of 2023).	**ALGERIA** - National Climate Plan (2018). A plan preceded by a Risk and Vulnerability Analysis (RVA) for climate change, mobilising tools and methodologies applied on an international scale. Includes more than 70 action measures that cover the transition to cleaner energy sources, the expansion of forest areas, and electrification of railway transport. - National Action Plan for the Environment and Sustainable Development (PNAEDD). - National Strategy for Integrated Waste Management (SNGID). **EGYPT** - Updated Nationally Determined Contributions (NDCs) (2030). - National Climate Change Strategy 2050: sustainable low-emission economic growth, build capacity to adapt to climate change and reduce the negative impacts of climate change, improve governance in the field of climate change, strengthen the role of research and technology in the field of climate change, improve green infrastructure and promote green economy activities, climate change risk management programme. **MOROCCO** - National Plan Against Global Warming (PNRC) (2009).[12] **TUNISIA** - National strategy for the adaptation of Tunisian agriculture and ecosystems to climate change (2012).[13] - Programme for Adaptation to Climate Change in Vulnerable Rural Territories of Tunisia (PACTE) (2017–2022). - NDCs submitted to UNFCCC in 2021. - National Strategy for Sustainable Development (NSSD) (2014). - Disaster risk reduction policy 2015–2030.

12 The stated aim is to "protect water resources against the impacts of climate change and improve the living conditions of rural populations through sustainable resource management".
13 The objective is to contribute to the sustainable development of Tunisian agriculture through the development and implementation of a set of mechanisms for the continuous adaptation of the agricultural sector and natural resources to climate change.

Main WEFE policies in EU and non-EU countries of the Mediterranean region			
	EU	**Middle East**	**North Africa**
FOOD (and soil)	- Common Agricultural Policy (2023–2027). - Green Deal: · Farm to Fork Strategy · Soil strategy for 2030 · Common Fisheries Policy · Long-term vision for Rural Areas	- Mediterranean Strategy for Sustainable Development. - Barcelona Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean. - MENA Food Security Strategy (2014). - MENA Sustainable Agriculture and Rural Development Initiative (2012).	**ALGERIA** - Development of Saharan agriculture, production cooperatives, food security; promotion of technical innovations (digitalisation and creation of start-ups). **EGYPT** - 2030 Sustainable Agricultural Development Strategy: sustainable management and preservation of resources (management of irrigation water and the recycling of agricultural waste as a source of income in rural areas), current agricultural policy encourages the abandonment of sugarcane cultivation in favour of sugar beet (less water consuming). **MOROCCO** - New agricultural sector development strategy, "Generation Green 2020–2030" "giving priority to the human element, to bring about the emergence of an agricultural middle class (350,000 to 400,000 households)"; new generation of young entrepreneurs, through the mobilisation and development of one million hectares of collective land and the creation of 350,000 jobs for young people; digitalisation and creation of start-ups. **TUNISIA** - Towards a new agricultural policy: Development Plan 2023–2025. "New Tunisian agricultural green deal".

Main WEFE policies in EU and non-EU countries of the Mediterranean region			
	EU	**Middle East**	**North Africa**
ECOSYSTEMS	- Forest Law Enforcement Governance & Trade Action Plan (2003). - Habitats Directive - Birds Directive. - Forest strategy for 2030. - Biodiversity strategy for 2030. - Nature restoration law (under negotiation, EC proposal). - Pollinators Initiative. - Strategy on adaptation to climate change. - Strategy on green infrastructure.	- Mediterranean Action Plan. - MedWet Initiative. - Mediterranean Forest Strategy. - Arab Strategy for Disaster Risk Reduction, adopted in 2018. - The Arab Strategy for Sustainable Agricultural Development, adopted in 2007	**ALGERIA** - National Action Plan for the Environment and Sustainable Development (PNAEDD) (2002). - National Strategy for the Environment and Sustainable Development (SNEDD) for the period 2017–2035, which constitutes the strategic reference document in the field of the environment. - Forest strategies: National Forestry Development Plan, National Reforestation Plan and National Protected Areas Management Plan. - Conservation strategy for natural ecosystems in arid zones in Algeria. - National Plan to combat desertification. - Strategy and National Action Plan for Biodiversity (SPANB). **EGYPT** - Sustainable Development Strategy to 2030: sustainable management of natural resources, reduction of pollution and sustainable waste management, reservation of ecosystems and biodiversity. **MOROCCO** - National Climate Plan 2020–2030 (NCP) which aims to establish the fundamentals of low-carbon and climate change resilient development. Organised around five pillars: establishing stronger climate governance, strengthening resilience to climate risks, accelerating the transition to a low-carbon economy, including territories in the climate dynamic, strengthening human, technological and financial capacities. **TUNISIA** - National strategy for water and soil conservation by 2030. - National Plan for Adaptation to Climate Change and Strategy for Resilient Development (SNRCC) under preparation. - Nationally Determined Contributions (NDC) (September 2015). - National Drought Plan (November 2020). - National Action Programme to Combat Desertification. - National Strategy for the Development and Sustainable Management of Forests and Rangelands, 2015–2024.

Table 5.1 | Main WEFE policies in EU and non-EU countries of the Mediterranean region.

5.2 Governance

5.2.1 Key actors and stakeholders in WEFE governance and dynamics

In recent years, the nexus concept has been gaining ground, providing an opportunity to shift IWRM from a sectoral focus to improving cross-sector efficiencies, considering telecoupling impacts and accomplishing cross-cutting objectives (Hindiyeh et al., 2023; Hoff, 2011; Taylor-Wood & Fuller, 2017). This shift has many implications for governance. Indeed, the approach gives equal importance to each sector and aims to better account for the trade-offs and synergies involved in meeting future demand for interconnected resources (Kahil et al., 2019). From this perspective, the WEFE nexus expresses the mutual interlinkages of the water, energy, and food sectors, and specifies how they depend on, and impact, ecosystems (e.g. forests, wetlands, grasslands, etc.). In line with the holistic approach of the SDGs, the WEFE perspective enables us to focus on achieving human well-being, poverty reduction and sustainable socio-economic development, rather than a narrower objective (Bervoets et al., 2018; Pistocchi et al., 2022) (see *Chapter 4*).

The nexus concept has been widely debated with regard to its impact on WEFE governance, especially in the policymaking arena, since 2011. This is a holistic way of thinking that considers long-term implications across the four nexus components, simultaneously balancing socio-economic and environmental objectives. While debate is ongoing regarding the meaning and application of the nexus concept, since reflexion and construction is still underway to achieve balance between the four components (Zhang et al., 2018), there is a common fundamental agreement about the importance of the approach (Simpson & Jewitt, 2019b) and the various governance implications it may trigger.

Undeniably, WEFE governance is a polycentric system, with diverse and varying decision centres or actions within sectors, which means identifying independent and overlapping key state and non-state actors – governments (acting through different ministries and public institutions), subnational (local and regional) authorities, civil society organisations, private sector, citizen groups, funders (e.g. PRIMA), multilateral and regional organisations (e.g. FAO, Plan Bleu, UfM, UNECE, etc.), national and international research institutions (Association of Agricultural Research Institutions in the Near East & North Africa (AARINENA), CIHEAM, Center for Mediterranean Integration (CMI), CNRS, European Commission's Joint Research Centre, Global Water Partnership-Mediterranean (GWP-Med), IRD, etc.), and national and International Development Agencies (e.g. ENABEL, GIZ, SIDA, USAID, etc.). WEFE governance requires that their respective roles become embedded in relevant policymaking processes, and that their goals, values, transactions and strategies support nexus related challenges and are continuously monitored and adjusted to meet their potential for enhancing WEFE dynamics. The various state and non-state stakeholders are building cooperative agreements and dialogue platforms to connect together, enhance and mainstream WEFE governance. WEFE governance also requires sound governance of each of its components, and implementation of the mechanisms required for achieving it, as for instance the implementation of IWRM in the case of water governance.

WEFE governance is not a matter of defining or creating new institutions. It is more about how existing institutions and actors at all scales and regions are empowered, strengthened, managed and interlinked. In other terms, the WEFE nexus requires ensuring that the existing governance settings integrate all other mechanisms and frameworks to encourage more coherence and collaboration between actors and their respective strategies and actions (Mohtar & Daher, 2014). For example, the principles, processes and obligations arising from IWRM or the Convention on Biological Diversity need to be integrated across all regimes. It is then necessary to reduce WEFE nexus knowledge gaps for all stakeholders.

However, on the ground, the various actors involved in WEFE governance need to develop or organise dialogue and review their missions (including strengths and weaknesses), and the extent to which they adopt a synergistic and integrated approach in order to develop consistency between nexus strategies and actions, while simultaneously avoiding or reducing nexus trade-offs and heterogeneity and strengthening legacy effects and institutional interlinkages (Malagó et al., 2021). In this regard, optimal policy mixes and governance arrangements across sectors, scales, and regions are those that accomplish all the policy objectives, rather than just selected ones. The complex links between the four WEFE nexus components need to be systematically integrated into the policy and project design or evaluated using a more holistic approach, which considers all stakeholders, including policymakers and advisors, civil society and private investors (Adamovic et al., 2019; Terrapon-Pfaff et al., 2018).

Discovery of policy mixes is a context-based process, with key elements of their identification and development being integration of policy objectives and ambitions (Glass & Newig, 2019; Jung et al., 2021) and participation of local stakeholders (Norström et al., 2020). Attention also needs to be paid to dynamics between policy instruments and their interactions (Kanger et al., 2020). When adequately developed, the nexus approach has the potential to simultaneously improve water, energy, food security, and ecosystem health by increasing the resource use efficiency, reducing trade-offs, strengthening synergies, and enhancing sustainability and governance across sectors (e.g. agricultural, health and industrial), boundaries, and scales (in time and space) (Hindiyeh et al., 2023; Malagó et al., 2021).

5.2.2 Coordination and cooperation between actors at all levels and scales of WEFE governance

In a world that has transgressed boundaries of safe human development (Persson et al., 2022; Steffen et al., 2015), pathways for a more sustainable future require an immense shift towards co-developing and scaling innovations and solutions that are more sustainable and systemic than conventional ones (Kılkış et al., 2020). The Mediterranean region is one of the most vulnerable regions in the world, presenting a large spectrum of problematic issues ranging from water pollution (Malagó et al., 2019) and natural resource degradation to water scarcity, large amounts of food loss and waste, and increasing demand for energy and food (Markantonis et al., 2019).

A sustainable and secure future in the Mediterranean area requires consistent and effective cross-cutting policies, which need coordination and cooperation across actors, places, scales and issues, and must address the indirect and hidden drivers underlying sustainability issues (Visseren-Hamakers et al., 2021). Existing policies and allied dynamics for negotiation and cooperation should enable better understanding of nexus interdependencies, which are critical for the development of a sustainable, secure, and resilient future in the Mediterranean region. These coordination mechanisms are of great importance and are crucial to achieving human security, well-being, poverty reduction and sustainability (Simpson & Jewitt, 2019a). In other words, strong coordination at the regional and local levels will help alleviate the huge challenge of development and societal issues and achieve the SDGs.

Another option could be to manage the water-energy-food nexus on an integrated geographical scale and consider comparative advantages as a nexus-smart opportunity at sub-regional and regional levels. As the WEF nexus approach aims to support policy and decision-makers in managing resource trade-offs across different economic sectors and actors, adopting such an approach by taking into consideration comparative advantages between countries could help securing water, energy and food at different levels. When complementarities and synergies between the three sectors cross national borders, potential WEF nexus net benefits may increase (Abulibdeh & Zaidan, 2020; Carli & Quagliarotti, 2022).

5.2.3 Science-Policy Interface (SPI) as one way of reinforcing coherence

There is a scarcity of literature with concrete nexus implementation practices, and few studies report real nexus application (e.g. Hoff et al., 2019; Malagó et al., 2021; Pistocchi et al., 2022). This can be explained by a number of constraints, such as insufficient incentives and limited vision, knowledge, development and investment, as well as insufficient empirical evidence of the potential benefits of the WEFE nexus approach (Hoff et al., 2019). It could also be due to insufficient understanding of nexus trade-offs within science-policy-stakeholder interactions (Liu et al., 2020).

Given the importance of dealing with climate change as a risk amplifier within the nexus, as shown in *Chapter 2*, uncertainty regarding climate events poses significant challenges to nexus governance systems in various ways. These include challenges to planning and decision-making, challenges to resource management, and challenges to social cohesion and equity (Termeer et al., 2012).

In the Mediterranean Basin, in addition to the above-mentioned constraints, and due to complex challenges, there is customarily an insufficient level of cooperation and integration between science and policy, especially in southern countries. Focus on science as a tool for overcoming poor integration has arisen in recent years in the Mediterranean region (Penca, 2021), particularly in the environmental area (Plan Bleu, 2018). This provides an opportunity to foster linkages in various forms, governance levels, and scope of interaction between different types of knowledge (scientific and "non-scientific", such as traditional knowledge and practices) and decision-making and policymaking processes relevant to the WEFE. Within such a perspective, and by reference to the science-decision interface, the WEFE approach needs to operate at the appropriate level of decision-making, mainly country- or region-based, without however excluding integration across national borders when the benefits are evident.

Universities and research organisations serve as knowledge generators and brokers and could integrate nexus thinking and organised policy dialogue into their research agendas and curricula. Governments and other institutions could improve or build their dialogue capacities and decision-making processes as well as strategic partnerships (Markantonis et al., 2019). Research priorities and aims, scales, technologies, models and data availability could be developed in order to reduce knowledge gaps and increase WEFE solutions and innovation. In this regard, there is a need to enforce WEFE nexus thinking within the SPI and relate it to SDG implementation and tracking. Also, society and associated grassroots NGOs could have a key role in WEFE governance and decision-making, implementation, and evaluation. At the same time, it is necessary to remove existing barriers and strengthen triggers to ensure the shift is optimal (Adamovic et al., 2019).

Ensuring the long-term health of global environmental commons requires a strong commitment. Science and academia, society and citizens, public and private sectors – what is called quadruple helix– should join forces to bridge existing gaps and develop a unique language to decomplexify the WEFE nexus and ensure awareness and implementation for higher economic growth and increased resilience and security (de Roo et al., 2021). All stakeholders, including decision makers, need to act based on deep and reliable knowledge and understanding of the linked pillars at all levels. There is a need to make WEFE interactions and trade-offs visible in order to reinforce or develop governance structures (Voelker et al., 2022).

To further streamline efforts, a profound and intentional departure from business-as-usual models is needed, and substantial changes are required from stakeholders in implementing the WEFE nexus and developing its metrics in line with the SDGs. Multiple entry points for getting away from business as usual have been recognised, including enabling approaches (Scoones et al., 2020). These include science/knowledge and technology as agents of change. The Science-Policy Interface (SPI) should set frameworks and tools that can be applied to facilitate decision-making at all levels and scales. In this regard, an open and inclusive assessment of the Mediterranean WEFE nexus SPI structure, processes, and skills, based on the categorisation in the Global Sustainable Development Report (Independent Group of Scientists appointed by the Secretary-General, 2019), is recommended. Such an assessment will make it possible to draw out key recommendations for strengthening and future enhancement of the SPI. In order to support the SPI, levers of transformation should be enforced, including multidimensional transfer of technology approaches, and technology should be facilitated and receive appropriate long-term funding.

5.2.4 Enhancing WEFE governance and a transformative framework

In the Mediterranean Basin, potential success stories for the implementation of good nexus practices have shown a focus on the use of suitable technologies and practices, but the nexus approach involves more than technical and economic efficiency (Malagó et al., 2021). The WEFE concept draws attention to the link between different environmental and societal areas, and potentially entails substantive shifts in, and transformation of, governance processes.

In this perspective, the WEFE is attracting new interest from scholars, policymakers, and development agencies across the Mediterranean, but disparities across countries and regions are still considerable. For the transition to sustainability, governance and a country's investment play a central role in driving change in WEFE metrics and SDGs. There is therefore a need to avoid siloed approaches and hierarchies and focus thinking on hybrid governance modes and policy instruments that are more appropriate for better management of WEFE challenges and interlinkages.

In this regard, the notion of "transformative governance" promotes a set of principles to support integration, inclusivity, empowerment, reflexivity and pluralism (Visseren-Hamakers et al., 2021). A transformative framework combines procedural and substantive aspects of biodiversity benefits (Penca, 2023), where governance goals should specifically target equality and inclusion of marginalised stakeholders as well (New et al., 2022). Concepts such as societal resilience, well-being and livelihoods can be useful, as well as a synergistic implementation of consensually agreed goals, such as SDGs promoting inclusive sustainable development or the Kunming Montreal Framework for Biodiversity focusing on living in harmony with nature. External linkages could worsen or sustain WEF resources and may significantly be affected by the nexus boundaries (ecological and technical components).

5.2.5 Deliberative democracy

Current democratic systems lack efficiency in adequately responding to the climate crisis and are insufficiently implementing climate plans to meet the goals of the Paris Agreement, for which the nexus components play a significant role both in terms of mitigation and adaptation (see *Chapter 3*). Political scientists identify several reasons for this failure, including (1) issues of temporality, or the ability of democratic decision-making to consider the medium- to long-term; (2) the way in which technical, scientific, and expert advice is used in the political process; and (3) questions of power, and the influence of entrenched interests on political decisions; and (4) the extent to which citizens' views and values are considered in democratic decision-making (Willis et al., 2022). To overcome some of these barriers, public authorities are increasingly using deliberative processes to involve citizens more directly in solving policy challenges. Deliberative approaches are some of the most innovative methods of citizen participation with the potential, according to some evidence, to help public authorities take difficult decisions on a wide range of policy issues (OECD, 2020; PACE, 2021). When conducted effectively, deliberative processes can lead to better policy outcomes, enable policymakers to make hard choices and enhance trust between citizens and government (OECD, 2020).

For the OECD (2020), they are part of a bigger picture of the systemic change that is needed and should be institutionalised, since they have the potential to help address some of the key drivers of democratic malaise in dealing with complex and long-term problems such as climate change; the need for careful use of scientific and technical evidence; the disproportionate influence of powerful political interests; and the distance between politicians and the citizens they represent (OECD, 2020; PACE, 2021; Willis et al., 2022). Deliberative approaches are also reflected in the United Nations 2030 Agenda for Sustainable Development Goals, with Goal 16 mentioning "responsive, inclusive, participatory and representative decision-making at all levels", and the United Nations Security Council, calling for "people action" as part of the "decade of action" from 2020 to 2030. In 2021, the Parliamentary Assembly of the Council of Europe urged governments "to combine a clear political engagement and top-down leadership with bottom-up, participatory governance, to tackle the urgency of the climate crisis and ensure meaningful contributions from citizens" (PACE, 2021). An important element of deliberative approaches is that despite the fact that while they focus on facts, and require consideration of evidence and the vital input of scientific and technical information into the decision-making process, they also recognise that political decisions cannot be reduced to technical considerations. Deliberative approaches acknowledge the existence of a variety of sources and forms of evidence as well as the value of knowledge from differently situated actors, particularly those most vulnerable to the impacts of climate change (Hammond, 2020), and they make explicit the consideration of moral and ethical positions in decision-making.

Deliberative processes therefore work well for: (1) values-driven dilemmas; (2) complex problems that require trade-offs; and (3) long-term issues that go beyond the short-term incentives of electoral cycles (PACE, 2021). This is the case for WEFE management in the context of climate change, where different response options may lead not only to different cascading effects, but also to different impacts on different social groups. This is particularly true for marginalised groups such as women or different ethnic groups. Hindmarsh (2008) assessed the relevance of deliberative approaches for water, energy and ecosystems management to avoid unintended consequences of policies and deliver options which are more inclusive with fewer trade-offs. He states, "people desire to be involved in debates about the life politics areas to be reassured that the ethical, social, health and environmental implications are carefully considered by, and incorporated into, decision-making." (Hindmarsh, 2008, p. 190). Smith (2003) proposed that the enhancement and institutionalisation of democratic deliberation will improve reflection on the wide range of environmental values that citizens hold.

One emerging type of deliberative democracy is citizens' assemblies (CA). They take place on all political levels, from local to international (PACE, 2021). They have four broad characteristics: (1) members are selected through random sampling and this is often weighted along socio-economic criteria, to enable the inclusion of a broad range of perspectives and experiences and to ensure that no social group is excluded, so that they are as representative of the broader population as possible; (2) they involve a learning phase, often receiving scientific input or supported by experts in the related field, allowing participants to consider evidence to develop their understanding of the issue in question; (3) deliberation, typically led by trained facilitators; and (4) the production of conclusions or recommendations. CAs usually meet over several months or years (PACE, 2021; Willis et al., 2022). For governments, citizens' assemblies can help address politically contentious issues. They can increase the legitimacy of political decisions and actions; indicate the willingness of citizens to accept potentially controversial policy interventions, and provide useful information on people's preferences and what compromises they are ready to make (PACE, 2021; Willis et al., 2022). For participants, they can represent a unique learning environment and harness a sense of pride in contributing to national decision-making (PACE, 2021). For citizens, the knowledge that policies have been proposed by people like themselves, having gone through an intense process of learning and deliberation, may increase trust and confidence in recommendations (Willis et al., 2022).

Contrary to what might be expected, citizens are widely open to behavioural change, and numbers are particularly high in countries where the effects of climate change are most frequently felt, such as the Mediterranean countries. The European Investment Bank Climate Survey (EIB, 2023), found that 72% of EU citizens are aware that their own behaviour can make a difference in tackling climate change, broken down as follows for Mediterranean European countries: 86% Portugal, 80% Spain and Italy, 78% Malta, 77% Slovenia, 71% Cyprus, 69% Greece, 65% Croatia, 63% France. 66% of EU citizens would be in favour of stricter government measures imposing changes in people's behaviour to tackle climate change, and again the numbers are higher than average in European Mediterranean countries (84% Portugal, 77% Slovenia, 76% Malta and Italy, 75% Croatia, 74% Spain, 72% Cyprus, 67% France, 66% Greece). Behavioural changes affecting the WEFE may include labelling all food in order to limit climate change and environmental impact, to pay extra for locally produced food with a lower impact on the environment or limiting the consumption of meat and dairy (*Figure 5.2*). It is therefore not surprising that national climate assemblies have developed positions which are more ambitious, and offer a more comprehensive response to the climate crisis than national governments (Willis et al., 2022). Lage et al. (2023) analysed the mitigation policies proposed by all the national climate assemblies run up to now globally, including France and Spain, and found that compared to National Energy and Climate Plans (NECP), the CA recommendations included a higher share of sufficiency policies (factor three to six; *Figure 5.3*) with a stronger focus on regulatory policies. Numbers were particularly high in the agriculture and nutrition sector as compared to the NECP. Indeed, despite the growing body of scientific evidence supporting sufficiency as an inevitable strategy for mitigating climate change, together with efficiency or the expansion of renewable energy, sufficiency plays a minor role in existing climate and energy policies. In terms of types of instruments, members of the CAs proposed

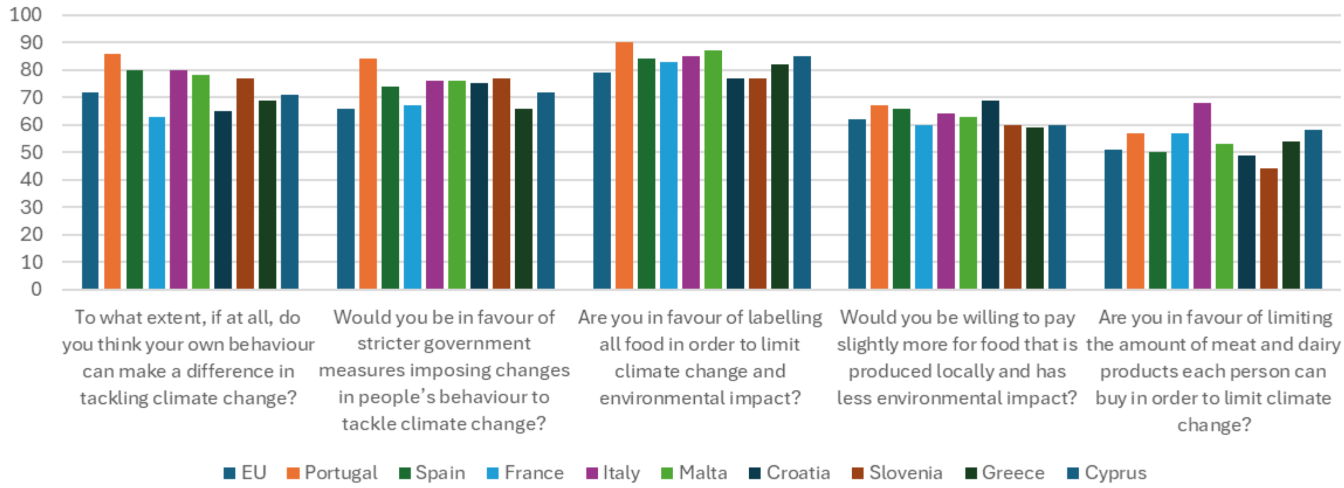


Figure 5.2 | Attitudes towards behavioural change in Northern Mediterranean countries (in %).
Source: own elaboration based on EIB (2023).

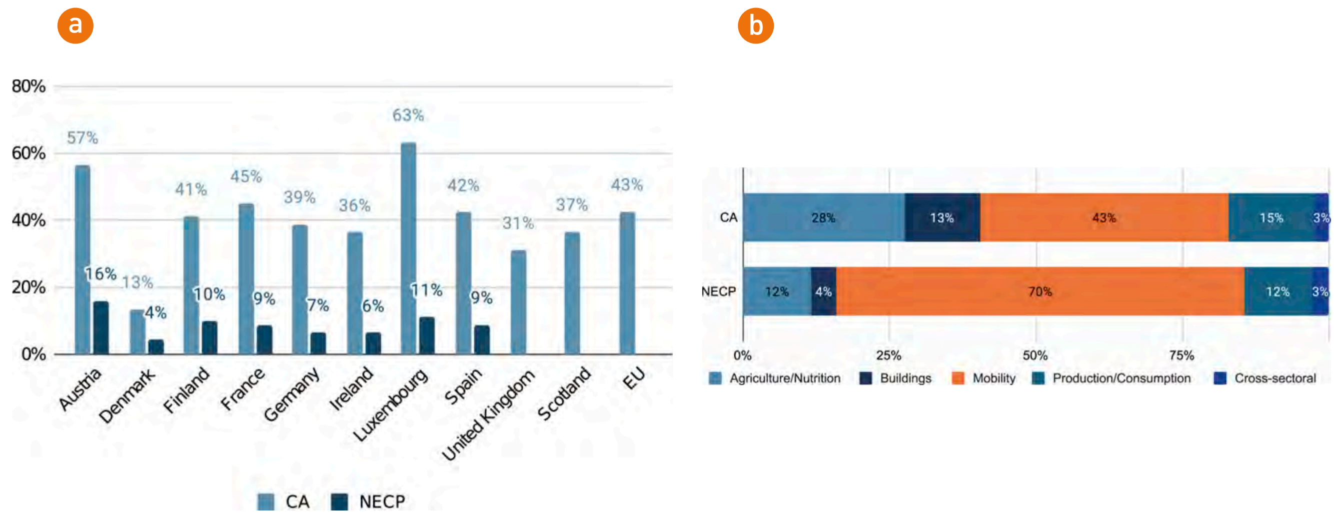


Figure 5.3 | (a) Share of sufficiency policies in total climate-mitigation policies from Citizens Assemblies (CA) and National Energy and Climate Plans (NECP) by country (UK, SC and EU did not submit a NECP). **(b) Sufficiency policies from CAs and NECPs by sector.**
Source: Lage et al. (2023).

regulatory policies more often than any other instrument type (34 %) and in a significant way for all sectors, as opposed to NECPs (11 %). In contrast, NECPs tend to rely more on fiscal and economic instruments. The share of "other" instruments, which include a number of policy plans that do not clearly specify instruments, is three times higher in the NECPs. Lage et al. (2023) state that CAs' recommendations can be interpreted as a call for a sufficiency turn and a regulatory turn in climate mitigation politics, suggesting that the observed lack of sufficiency in climate policymaking is not due to a lack of legitimacy, but rather reflects a reluctance to implement sufficiency policies, the constitution of the policymaking process and competing interests.

5.3 Factors enabling the WEFE nexus approach

5.3.1 Supporting research for technological and social innovations

Innovation, in the context of the WEFE nexus, must be considered with a systemic approach, as innovation in one of the WEFE pillars is likely to impact the others. (e.g. Bazilian et al., 2011) (see *Chapter 3*). Given the correlation between water, energy, and food prices (Chen et al., 2010), any regulation in one of these sectors would trigger sustainable innovations in the others. This effect, known as the weak Porter hypothesis, would be intensified by the existence of knowledge spillovers between water-, energy-, food- and ecosystem-related technologies.

Over the last decade, innovations have tended to be less area-specific to address the broader systemic challenges raised by the nexus, with a particular focus made on improving agricultural and energy production resilience to water scarcity (Sarni, 2015). Different types of innovation related to the WEFE nexus have been implemented in the Mediterranean region: they may be broadly categorised into technological innovation and social innovation (see *Chapter 3*). Technological innovations include the development of new or improved technologies for managing and conserving WEFE resources (e.g. (Yuan & Lo, 2022). Social innovations include new approaches to policy, financing, governance, and other social systems that can facilitate the adoption and diffusion of new technologies, organisational forms or practices in the WEFE domains. Examples of social innovations include new business models, community-based approaches to resource management, and policy initiatives that promote sustainability and equity. For instance, co-housing or ecovillages can potentially reduce the environmental impact of households by fostering shared and responsible consumption of water, energy and food and integrated management of such resources (Daly, 2017; Pérez-Sánchez et al., 2022). Other types of social innovation include organisational innovations, such as new partnerships or collaborations between different stakeholders, and cultural innovations, such as new values or behaviours that support the sustainable use of WEFE resources. For instance, the urban roofs developed in densely populated Mediterranean cities provide food, energy, water, and environmental services and thus address the complexity of the nexus (Toboso-Chavero et al., 2019, 2021).

Several organisations have innovated on how they address the nexus issue (Hertel & Liu, 2016). Technological and social innovations along the WEFE nexus should focus on:

- optimising the use and efficiency of WEFE resources;
- ensuring resource security at national and global levels, including access to WEFE to address environmental change and adapt societies to change;
- enabling the achievement of the Sustainable Development Goals (SDGs), by offering support for decision-making with proper monitoring of progress using relevant indicators; and
- consolidating integrated infrastructure for supporting multiple sectors and enhancing the opportunities and benefits of innovative technologies.

The first EU-Med Ministerial Conference on Higher Education and Scientific Research held in Cairo in 2007 endorsed the implementation of coordination activities for the EU-Med region, under the Seventh Framework Programme for Research. This is how the first two ERANET5 programmes, ARIMNET (in 2009) and ERANETMED (in 2012), were implemented, launching seven transnational calls for proposals in the fields of agriculture, water, food and energy (Zebakh et al., 2022). The two programmes funded 96 transnational projects. Results show that 73 projects (76 %) directly address interaction between at least two WEFE sectors. These projects offer sustainable technological approaches and solutions to impact the European and Mediterranean ecosystems. ARIMNET projects are mostly related to the food-ecosystem nexus (*Figure 5.4)*. ERANETMED programmes focus more on WEFE interactions, in particular on water-ecosystem interactions (38.5%) and energy-ecosystem interactions (15.4%). This differentiates it from the ARIMNET programme. The PRIMA programme is launching annual calls for innovative research proposals covering four thematic areas, one of which is dedicated to the WEFE nexus. PRIMA aims to build sustainable connections by mainstreaming the WEFE nexus approach into PRIMA's future calls. By mainstreaming the WEFE nexus approach into all PRIMA's topics and thematic areas, PRIMA aims to promote the development of innovative solutions that address the complex

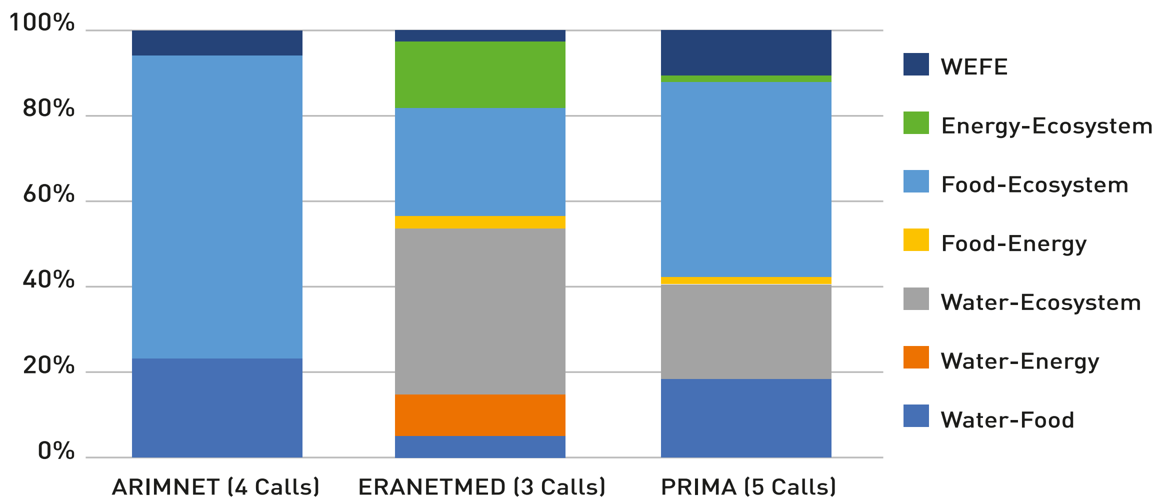
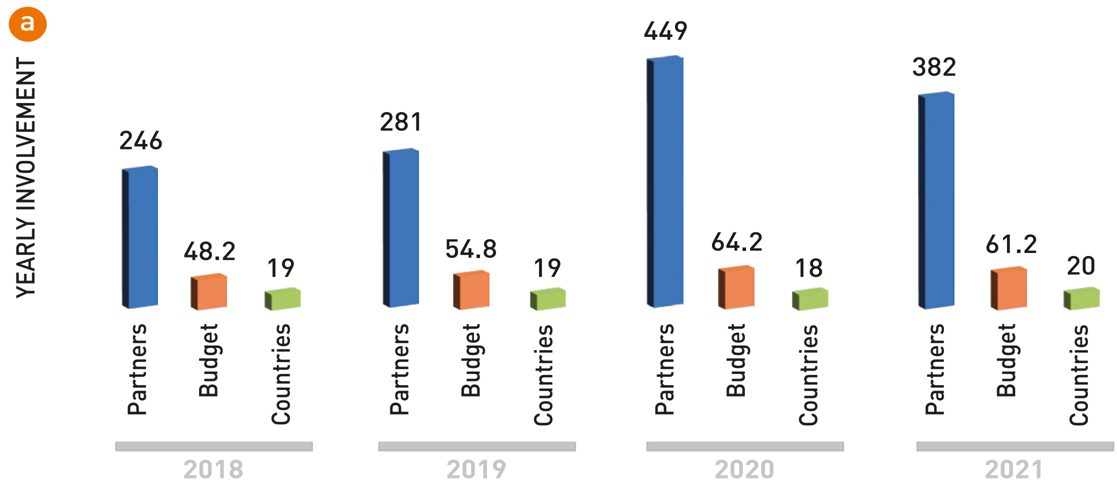
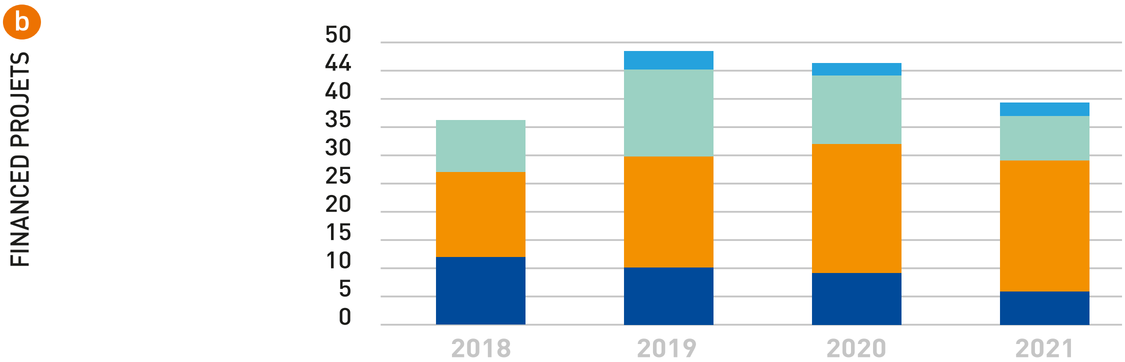


Figure 5.4 | Water-Energy-Food-Ecosystem nexus in EU-MED research programmes.
Sources: ARIMNET, ERANETMED, PRIMA.





	2018	2019	2020	2021
Multisectorial		3	2	2
Agri-food value chain	9	15	12	8
Food-systems	15	20	23	23
Water management	12	10	9	6

Figure 5.5 | PRIMA Foundation "Partnership for Research and Innovation in the Mediterranean Area" in numbers.
Source: PRIMA (2018, 2019, 2020, 2021).

interconnections between water, energy, food, and ecosystems. PRIMA has built numerous partnerships with different actors. In 2018 alone, they supported 36 projects in the fields of water management and food systems including the entire agrifood value chain. Implementation of these projects received a total budget of €48.2 million and involved 246 partners which included multiple countries' governmental institutions (such as Ministries for Education), research centres, universities and private partners (e.g. consultancy firms, cooperatives, agrifarm industries). Those numbers increased in 2019 and have only slightly been impacted by the Covid era (2020–2021) highlighting the relevance of the WEFE nexus topic (PRIMA, 2018, 2019, 2020, 2021; *Figure 5.5*).

A concrete shift towards sustainability would entail nexus collaborative models or processes becoming part and parcel of development planning at local, regional and national levels. To do so, high-level political will, supported by a sound governance system and informed by science and data are key to ensure that the WEFE nexus is integrated and mainstreamed in planning, monitoring and evaluation systems at all levels.

5.3.2 Capacity-building and awareness-raising

WEFE nexus discussion and applications are mainly focused on global or national scales and on macro-level drivers. This approach neglects the fact that major challenges related to the WEFE nexus are faced at the local level. The responsibility to operationalise the WEFE nexus, at the micro level, falls on institutions, communities, small businesses, and households (*Box 5.1*). This is the first barrier to the implementation of the WEFE nexus. The engagement of all the key actors of the Mediterranean region is an essential element for the WEFE nexus approach, given its demand for strong cooperation and mutual trust (Markantonis et al., 2019). A second limitation of many, is the existence of structural and process asymmetries that lead to a lack of coordination between the main stakeholders and other external influences (Alamanos et al., 2022). These are major obstacles to building the long-term confidence and trust of citizens (Nardi & the NEXUS-NESS Consortium, 2022), but they are not the only ones. Missing information exchange and lack of collaboration across WEFE nexus resource boundaries are also issues (Jones & White, 2022), leading to the persistence of strong sectoral silos (Hoff et al., 2019). Undeniably, multi-sector, multi-disciplinary, and multi-actor approaches are currently not systemically incorporated into decision-making (Nardi & the NEXUS-NESS Consortium, 2022). The picture is even more problematic when national boundaries are, and need, to be overcome. For example, due to the specific conditions of the region and sub-regions, it is difficult to establish a dialogue network appropriately involving local stakeholders (Markantonis et al., 2019). The combination of a limited vision, lack of knowledge, and practical multi-sided experience hampers the successful implementation of the nexus approach within the awareness sphere (Hoff et al., 2019) and, this should be taken note of for the Mediterranean area.

To overcome these problems, there are some enabling factors that can be fostered (Yuan & Lo, 2022). Clearly, a first area of improvement should be stakeholder involvement (Lamonaca et al., 2022). Rather than one-way communication of research results, a multilateral exchange approach could be taken (Wade et al., 2020). Decision-making demands the inclusion of diverse stakeholder interests (Bielicki et al., 2019) so that their participation can lead to more innovative, decision-relevant and publicly-accepted solutions (Wade et al., 2020). This involvement can be achieved both horizontally and vertically (Hoff et al., 2019): citizens and stakeholders from a broad range of sectors and interest groups, including economy and finance, as well as from different levels of governance – like mayors, farmers, irrigation agencies, energy utilities, national government representatives – should be included (Flammini et al., 2014). Importantly, the private sector must be involved along with the public sector (Carmona-Moreno et al., 2021; Markantonis et al., 2019). The private sector plays a crucial role in fostering technological advancement through the implementation of novel approaches and best practices, thus facilitating the democratisation of data generation and the development of cost-effective solutions (FAO, 2022). Since interlinkages across sectors for an integrated approach in decision-making is not yet adequately reflected in policies, governments and policymakers need to address this as a priority political focus. FAO (2022, p. 4) underlines a good example in the MENA region which comes from the setting up "in 2019 by the League of Arab States of the High-Level Joint Water-Agriculture Technical Committee, with support from FAO and the United Nations Economic and Social Commission for Western Asia (ESCWA), and making the WEF Nexus one if its priority areas". For this to be feasible, key stakeholders need to be aware of and acknowledge the WEFE nexus and its challenges, in order to successfully tackle them.

As anticipated, communication must be enhanced in order to transfer information. A nexus-oriented platform for dialogue can be designed with versions for each specific context – local, regional, national – and for a transboundary, basin-level too (Flammini et al., 2014). As jargon is a barrier to broader collaboration, the terminology, paradigms, and theoretical frameworks need to be understood by all involved actors, with a view to the development of a shared language (Wade et al., 2020). An important asset to engage WEFE stakeholders, who all have different competing targets, is to implement a new framework that supports data transparency, which is key to generating trust (Piera et al., 2014). Strategically, the exchange of commonly understandable information is the basis not only for capacity-building activities, but also for setting agreements for sharing data and information systems (Markantonis et al., 2019) and for lowering the barriers to understanding nexus complexity (Howarth & Monasterolo, 2016).

This final aim can be a powerful tool as the integration of data, techniques, and methodologies from two or more disciplines helps to solve problems whose solutions are beyond the scope of a single area and need to be operationalised (Dalla Fontana et al., 2021). In fact, this is what the nexus is: a wicked problem (i.e. "a problem resisting definitive formulation and clear-cut solutions and whose complexity demands new modes of inquiry") (Wade et al., 2020, p. 1, citing Rittel & Webber, 1973). It follows from the nature of the nexus, and its requirement for deep integration across fields and transcendence of boundaries, that interdisciplinary teams and transdisciplinary methods should be brought into play (Balaican et al., 2023). A broader participation and enhanced incorporation of knowledge from various sources, such as academic research, on-the-ground practitioner experience, and civil society knowledge have to be integrated (Albrecht et al., 2018), since people's everyday experiences are often overlooked.

The younger generations will be most affected by changes in the resources covered by the nexus (Trajber et al., 2019). Future generations (as well as current ones) will need to employ systems thinking and learn to thrive in interdisciplinary teams with effective communication. These skills will prepare them to build innovative, actionable solutions and to successfully lead across a variety of dynamic challenges (Wade et al., 2020).

The above-mentioned problem of mutual trust between experts and the citizens can be explained by the objections to the knowledge-deficit model (i.e. the assumption that, if they knew more, non-scientists would integrate scientific information into their decision-making processes), largely refuted on the basis that people's perceptions and use of science are influenced by their beliefs and ideologies (Eveland & Cooper, 2013; Fiske & Dupree, 2014; Simis et al., 2016). To cope with this limitation, two strategies can be adopted, including at basin level. The first understands that the public, as traditionally interpreted, would be better reached by informative communications. Messages should be targeted to specific audiences and appropriate communication frames should be selected to resonate with the belief systems of the intended listeners (Wade et al., 2020). If science is communicated properly, by accounting for required adaptations, the public's appreciation and understanding can increase, achieving public support and commitment (Hannibal & Portney, 2019).

The second strategy is to assign an active role to the public, and not only a passive one. Participatory approaches are very useful tools for improving decision-making processes in complex systems. Since the object of study is a wicked problem, they make it possible to co-produce and co-test avenues by assisting and enabling stakeholders to examine the implications of possible future changes and to navigate emergent difficulties and opportunities so as to address environmental challenges effectively (Larkin et al., 2020). These exercises can include different types of activities such as community of practice, role-play games, demonstration sites and living labs carried out or integrated through workshop events, meetings and also lessons that contribute to this task (*Box 5.2*). Citizens' assemblies can play a relevant role here. The general advantages

Box 5.1

The WEFE nexus at the household level

Recent studies have started to explore the dynamics and sustainability of the WEFE nexus at the household level by developing novel approaches such as the "Nexus at home" (Foden et al., 2019). However, empirical evidence grounded in the different Mediterranean regions required to extract tailored useful lessons and political implications about the household WEFE nexus is still incipient and fragmented (11.4% of nexus research by researchers affiliated with Mediterranean countries, particularly from the Northern Mediterranean - Itayi et al., 2021).

Available empirical evidence about the water and energy nexus at household level has highlighted the shared and accumulated difficulties of accessing and affording both resources – commonly known as basic services – by vulnerable families (Fankhauser & Tepic, 2007; Yoon et al., 2019). Water and food insecurity have also been studied in conjunction, particularly in low- and middle-income countries such as Lebanon, showing that household water insecurity is a fundamental driver of household food insecurity (Brewis et al., 2020; Stoler et al., 2020).

Unravelling the interlinkages and interdependencies between energy poverty, water poverty and food insecurity is therefore key to downscaling nexus approaches at local, community and household levels (Santeramo, 2021). The Mediterranean regions face crucial challenges regarding energy poverty, with implications for water and food access. While the dynamics and drivers of energy poverty have been increasingly and more systematically assessed for European Mediterranean countries (Bouzarovski & Tirado Herrero, 2017), recent research is covering other areas of the Mediterranean traditionally overlooked (El-Katiri, 2014) such as Türkiye (Dogan et al., 2021), Cyprus (Kyprianou et al., 2022), and Egypt and Morocco (Rao et al., 2022). This new situated knowledge will be key to identifying contextual factors and barriers to ensuring household's rights to energy, water and food across different geographies. Nevertheless, whenever focusing policies on local and indigenous communities, it is essential that affected stakeholders participate in all the decision-making processes that may impact their lands, resources, cultures, and livelihoods. Local communities have the right to prior and informed consent through engagement, transparency, and knowledge-sharing (FAO, 2015). The consent given to a project can be given and withheld before any decision is made, on the basis of detailed information provided in a format the stakeholders can understand (from a cultural perspective, i.e. language, and technicalities of the project).

Beyond the local context, other global and multiscale drivers and processes condition the food-energy-water interlinkages at home. On the one hand, climate change will intensify these multiple interlinked vulnerabilities shaping water, energy, and food domestic security (Živčič & Tirado Herrero, 2021). On the other hand, the recent energy crisis or the volatility of food and energy prices may aggravate situations of WEF vulnerability, but also offer opportunities for transforming policies towards alleviating vulnerability and improving security (Osička & Černoch, 2022; Santeramo & Lamonaca, 2021; Siksnelyte-Butkiene, 2022).

of these approaches can also be beneficial for Mediterranean communities. They are twofold: on the one hand, there is a contribution to understanding the nexus, enabled by the emergent co-production of knowledge, action and critique. By participating in the research process and testing and implementation phases, stakeholders may help guiding or redirecting research questions and study design so as to address real issues more directly (Albrecht et al., 2018). It is very important that the future nexus framework considers a human-centric approach in which citizens could transform their opinions into relevant knowledge through the use of friendly simulators and serious games (Piera et al., 2015). On the other hand, these participatory settings raise the awareness of involved actors. Stakeholder engagement hastens social learning – which leads to greater consensus and higher likelihood of solutions achievable through joint action (Collins & Ison, 2009), and also legitimacy of the actions. Furthermore, broader processes of engaging and discussing with key stakeholders and experts – including a nexus community of practice (NCoP) to promote this integrative approach (Mohtar & Lawford, 2016) – enables longer-lasting impacts (Flammini et al., 2014).

Finally, for the implementation of this kind of approach to stakeholder-related enabling factors, planning is needed. The requirement for a comprehensive stakeholder awareness roadmap and action plan should be supported and shared by all involved parties with the goal of developing the nexus approach at a local, but never disconnected, level (Markantonis et al., 2019).

Box 5.2

Examples of participatory approaches: living labs (LLs) and serious games (SGs)

Living labs (LLs) are *"open innovation ecosystems in real-life environments using iterative feedback processes throughout a lifecycle approach of an innovation to create sustainable impact. They focus on co-creation, rapid prototyping and testing and scaling-up innovations and businesses, providing (different types of) joint-value to the involved stakeholders. LLs operate as intermediaries/orchestrators among citizens, research organisations, companies and government agencies/levels"* (European Network of Living Labs (ENoLL)[14]– Living labs are an effective solution for providing a transdisciplinary, experimental process that can bridge the technical and social divide, helping to identify relevant solution pathways (Wahl et al., 2021). A good practice is the SUSTAIN adapt project[15], whose methodological framework aims to facilitate the engagement of key stakeholders (e.g. decision-makers, NGOs, civil society, private sector) and evaluate policy coherence through four LLs, one for each of the following sectors: agriculture, forestry, water resources, and urban settlement.

Serious games (SGs) are interactive games in which players perform activities that enable them to develop skills and achieve aspects beyond simply being entertained by the tasks (Djaouti et al., 2011). The Horizon2020 project, SIM4NEXUS, provides various examples (2016–2020): serious games investigating potential cross-nexus synergies for 12 multi-scale case studies where stakeholders and partners are involved from case study conceptualisation, quantitative model development and implementation and validation of each serious game (e.g. Balaican et al., 2023; Melloni et al., 2020; Sušnik et al., 2018; Zhang et al., 2021).

5.3.3 Innovative funding mechanisms

Given the intrinsic complexities of the WEFE nexus, and the increased challenges posed by climate change, urgent action is now required. All key actors at all levels must take part, and no stone should be left unturned. Sound governance and strong political will are the essential enabling factors for the assimilation of new objectives into the socioeconomic and financing context. On this last point, the OECD suggests integrating the SDGs into national plans, by considering the synergies between *"investment financing needs for water, agriculture and energy infrastructure"* (OECD, 2014, p. 11) and therefore the need to act accordingly when supporting projects. The expectation is that governments should act in support of "nexus-friendly" multi-purpose infrastructures, projects or policies by avoiding the creation of market distortions which, in turn, may work against the purpose (OECD, 2014).

Public policies are believed to be a first essential enabling factor for mobilising private financing (FAO, 2022; Wu, 2015). For this reason, the GISD Alliance (2020) has developed a definition of Sustainable Development Investing, to harmonise national approaches and therefore enable clearer communication between investors. On the basis of the Sustainable Development Investing principles, in order to foster technological innovation and the adoption of best practices, policymakers must involve the private sector and support stakeholders' projects through innovative strategies and tools such as de-risking, partnerships or by checking the quantity and quality of investments. In fact, financing mechanisms need to be defined to upscale proven solutions (FAO, 2022). The best-known economic instruments available to governments to incentivise or disincentivise certain behaviour are surely subsidies and taxes. Historically, these are widely applied when addressing the WEFE nexus with the aim of increasing desirable actions (such as research and development) or reducing the consumption of certain goods (e.g. water or energy). Nevertheless, such solutions are likely to hit only one nexus component, entailing only marginal benefits for the others. Public institutions are therefore now encouraged to put in place or facilitate innovative

14 European Network of Living Labs. Available at: www.enoll.org

15 https://www.cmcc.it/it/sustainadapt par www.cmcc.it/it/sustainadapt

financing mechanisms to promote appropriate business models and capacity-building in the private sector, or implement direct technical interventions (FAO, 2014):

- Blended finance: strategic use of development finance through the use of public resources to attract the private sector and mobilise additional finance towards sustainable development in developing countries. Its use aims to mitigate political and commercial risks by various instruments (OECD, 2018b). Given their focus on risk mitigation to attract a higher number of investors on more desirable projects (Carmona-Moreno et al., 2021), these practices are generally called de-risking and include, among others, co-investment, co-financing (where public actors provide equity or debt alongside private players), cornerstone stakes (public actors commit in advance to certain desirable investments as a demonstrative action) and loan guarantees (OECD, 2021). These instruments are expected to have a capital return at the end of the investing period. Clearly, to properly address the WEFE nexus, these approaches should not only involve multiple actors, but also multiple sectors. The UN encourages governments to engage and promote de-risking, in order to involve private investors in sustainable development projects (UN, 2021). Similarly, a combination of subsidies, tax incentives, leases of public land and blended capital solutions is a potential enabling strategy to develop large-scale agribusiness projects, compliant with WEFE nexus requirements, in the Mediterranean area (Markantonis et al., 2019).

- Green bonds and green bonds for climate resilience: Green bonds are issued by companies or governments to mobilise capital through the debt market in favour of low carbon and climate resilient investments (OECD, 2017). Similarly, green bonds for climate resilience issue capital for projects, which, at least partially, can support climate adaptation and increase the capacity to cope with physical climate risks (GCA, 2021). These could therefore be issued to fund adaptation projects addressing the WEFE nexus (e.g. multi sectoral water infrastructure) (GCA, 2021).

- Public-Private Partnerships (P3s): contracted partnerships between private and public entities to deliver a certain public service. Cooperation between the contracting parties is desirable whenever there is an imbalance between the involved actors in terms of knowledge, capacity or capital, but especially when there is a need to leverage resources to increase the commercial potential of solutions. To reach this final goal, P3s may also embrace blended finance tools (Carmona-Moreno et al., 2021).

Any of these innovative financing strategies should respect the principles of equality and sustainability: that is no one should be left behind, gaps should be filled, and actions should foster SDG achievement (OECD, 2020). In this context, P3s are particularly valuable solutions as they allow for extreme flexibility. They can be proposed and built both with a bottom-up or top-down approach (and can therefore respond to the needs of any actor of society), with any timespan and at any spatial scale. Moreover, they allow not only for cross-sectoral focus but also for multiple stakeholder involvement and exchange. For this reason, multiple studies on the implementation of WEFE projects indicate P3s as one of the most preferable solutions (FAO, 2022; Markantonis et al., 2019; Mayor Rodríguez, 2016). In fact, such inclusive solutions may be particularly effective in heterogeneous and fragmented areas, such as the Mediterranean, where the involvement of local actors is necessary to target specific needs.

Multiple strategies applied for the implementation of WEFE nexus projects at the Mediterranean Basin level show that project features, actors involved, and capacities need to be adapted to local vulnerabilities, in line with site specificities. Large foundations and consortiums in the area are particularly active as they can operate between multiple countries, involve different actors and, therefore, build synergies faster and more efficiently. Examples are PRIMA, the Partnership for Research and Innovation in the Mediterranean Area, which involves both EU and non-EU countries, the MENA Regional Innovation Hub (MENA RIH), operating exclusively in the MENA region, and the Interreg MED (now Interreg Euro-MED) and ENI CBC MED (now Interreg NEXT MED) programmes supporting the development of several territorial cooperation projects tackling some WEFE nexus components. The MENA RIH is an accelerator, empowering private businesses engaged in the WEFE nexus: projects must focus on increasing food production while reducing water and energy usage. In collaboration with investors and allies, the MENA RIH endeavours to grow mid-to-later stage businesses that have a positive effect on the environment and society within the water-energy-food nexus by offering investors different innovative financing solutions. Additionally, Mediterranean developing countries can access specific climate finance funding to address the nexus in the context of climate change, such as the Green Climate Fund, a fund established to support climate change adaptation and mitigation for developing countries with a view to the implementation of countries' Nationally Determined Contributions (UN, 2021). This is reserved for developing countries, and could be used by most Mediterranean states except for the EU-27, including Albania, Algeria, Egypt, Jordan, Lebanon, Libya, Montenegro, Morocco, North Macedonia, Syria, Tunisia and Türkiye.

So far, projects focusing on the WEFE nexus at Mediterranean level tend to effectively target the SDGs connected to the WEFE nexus and to provide significant benefits for society. Nevertheless, most tend to prioritise a single specific sector and therefore fail to create synergy effects (Malagó et al., 2021).

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Annexes

Annex I: Glossary

Notes

Most definitions in this glossary are sourced from the glossaries of the 6th IPCC Assessment Report (IPCC, 2021; IPCC, 2022a, IPCC, 2022b). The remaining definitions have been provided by the authors of this report. Please note that this list of terms is not exhaustive. For terms not included here, please refer to the glossaries IPCC and IPBES.

2030 Agenda for Sustainable Development: A UN resolution in September 2015 adopting a plan of action for people, planet and prosperity in a new global development framework anchored in 17 Sustainable Development Goals

Adaptation: In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

Afforestation: Conversion to forest of land that historically has not contained forests.

Agrivoltaics: A food-energy producing system that involves the simultaneous use of land areas for both solar photovoltaic (PV) power generation and agriculture.

Agro-inputs: Biological or chemical or inorganic compounds used in the production of agricultural and allied products.

Agrobiodiversity: The result of natural selection processes and the careful selection and inventive developments of farmers, herders and fishers over millennia.

Agrochemical: A chemical used in agriculture, such as a pesticide or a fertiliser.

Agroecology: The science and practice of applying ecological concepts, principles and knowledge (i.e. the interactions of, and explanations for, the diversity, abundance and activities of organisms) to the study, design and management of sustainable food systems, through forms of collective action, which explicitly considers economic, social, environmental and ecological aspects, based on traditional peasants' knowledge to promote endogenous development, but open to innovations that help sustainability. Agroecology examines the roles and interactions among all relevant biophysical, technical and socio-economic components of farming systems and their surrounding landscapes.

Agroforestry: Collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems, there are both ecological and economical interactions between the different components.

Air pollution: Degradation of air quality with negative effects on human health or the natural or built environment due to the introduction, by natural processes or human activity, into the atmosphere of substances (gases, aerosols) which have a direct (primary pollutants) or indirect (secondary pollutants) harmful effect.

Anoxia: An absence or deficiency of oxygen.

Anthropogenic: Resulting from or produced by human activities.

Anthropogenic emissions: Emissions of greenhouse gases (GHGs), precursors of GHGs and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use and land-use changes (LULUC), livestock production, fertilisation, waste management, and industrial processes.

Aquatic biota: All living organisms found in water environments, including freshwater (lakes, rivers, ponds) and marine (oceans, seas) ecosystems. This term encompasses a wide variety of life forms, from microscopic organisms like bacteria and plankton to larger species such as fish, amphibians, aquatic plants, and invertebrates like mollusks and crustaceans.

Arid zone: Areas where vegetation growth is severely constrained due to limited water availability. For the most part, the native vegetation of arid zones is sparse. There is high rainfall variability, with annual averages below 300 mm. Crop farming in arid zones requires irrigation.

Barcelona Convention: The Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean, originally the Convention for Protection of the Mediterranean Sea against Pollution, and often simply referred to as the Barcelona Convention, is a regional convention adopted in 1976 to prevent and abate pollution from ships, aircraft and land based sources in the Mediterranean Sea. The Barcelona Convention and its protocols form the legal framework of the Mediterranean Action Plan (approved in 1975), developed under the United Nations Environment Programme (UNEP) Regional Seas Programme.

Behavioural change: In this report, behavioural change refers to alteration of human decisions and actions in ways that mitigate climate change and/or reduce negative consequences of climate change impacts.

Biodiversity (biological diversity): The variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems.

Biodiversity hotspots: Biodiversity hotspots are geographic areas exceptionally rich in species, ecologically distinct, and often contain geographically rare endemic species. They are thus priorities for nature conservation action.

Bioenergy: Energy derived from any form of biomass or its metabolic by-products.

Biofuel: A fuel, generally in liquid form, produced from biomass. Biofuels include bioethanol from sugarcane, sugar beet or maize, and biodiesel from canola or soybeans.

Biomass: Organic material excluding the material that is fossilised or embedded in geological formations. Biomass may refer to the mass of organic matter in a specific area.

Business as usual (BAU): The term business as usual scenario has been used to describe a scenario that assumes no additional policies beyond those currently in place and that patterns of socio-economic development are consistent with recent trends. The term is now used less frequently than in the past.

Carbon cycle: The flow of carbon (in various forms, e.g. as carbon dioxide (CO_2), carbon in biomass, and carbon dissolved in the ocean as carbonate and bicarbonate) through the atmosphere, hydrosphere, terrestrial and marine biosphere and lithosphere.

Carbon dioxide (CO_2): A naturally occurring gas, CO_2 is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land-use changes (LUCs) and of industrial processes (e.g. cement production). It is the principal anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance.

Carbon footprint: Measure of the exclusive total amount of emissions of carbon dioxide (CO_2) that is directly and indirectly caused by an activity or is accumulated over the lifecycle stages of a product.

Carbon sequestration: The process of storing carbon in a carbon pool.

Cascading impacts: In this report, cascading impacts in the WEFE nexus occur when a driver of change (e.g. climate change) generates a sequence of secondary events in the WEFE components mediated by the interactions, synergies and trade-offs among them. They are linked to particular responses developed to achieve water, food, energy security or ecosystems health, whereby the resulting impact is significantly larger than the initial impact. Cascading impacts are complex and multi-dimensional, and they can be positive when synergies are promoted (nexus approach) or negative when trade-offs are predominant (silo approach) .

Circular economy: A system with minimal input and operational losses of materials and energy through extensive reduce, reuse, recycling, and recovery activities. Ten strategies for circularity include: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover.

Climate change: A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.

Co-benefits: A positive side-effect that a policy targeting one objective has on another objective. Co-benefits increase the total benefit to society or the environment.

Confidence: The robustness of a finding based on the type, amount, quality and consistency of evidence (e.g. mechanistic understanding, theory, data, models, expert judgement) and on the degree of agreement across multiple lines of evidence. In this report, confidence is expressed qualitatively.

Decarbonisation: Human actions to reduce carbon dioxide emissions from human activities.

Deforestation: Conversion of forest to non-forest.

Desalination (of water): Process of removing mineral components, salts and impurities from seawater or brackish water to produce freshwater suitable for human consumption, agriculture, or industrial use. This method is especially important in arid regions or areas with limited access to freshwater resources. Along with recycled wastewater, it is one of the few water resources independent of rainfall.

Desertification: Land degradation in arid, semi-arid, and dry sub-humid areas resulting from many factors, including climatic variations and human activities.

Diet: The kinds of food that follow a particular pattern that a person or community eats.

Drip irrigation: Irrigation method where water is delivered directly to the roots of plants in a slow, controlled manner. It involves a network of tubes or pipes with small emitters or drippers that release water at low pressure, ensuring minimal evaporation and runoff. This technique allows for precise water delivery, optimising water use.

Direct driver: Factors or processes that directly affect environmental conditions and ecosystems. These drivers can lead to changes in land use, biodiversity, water quality, and other ecological indicators. They often manifest as immediate and tangible impacts on the environment. Direct drivers can be of natural or anthropogenic origins.

Drivers of change: Factors that affect nature, anthropogenic assets, nature's contributions to people, and a good quality of life.

Drought: A period of abnormally dry weather long enough to cause a serious hydrological imbalance. **Hydrological drought:** A period with large runoff and water deficits in rivers, lakes and reservoirs. **Agricultural and ecological drought:** Agricultural and ecological drought (depending on the affected biome): a period with abnormal soil moisture deficit, which results from combined shortage of precipitation and excess evapotranspiration, and during the growing season impinges on crop production or ecosystem function in general. **Meteorological drought:** A period with an abnormal precipitation deficit.

Ecological footprint: The impact of a person or community on the environment, expressed as the amount of land required to sustain their use of natural resources.

Ecosystem: A functional unit consisting of living organisms, their non-living environment and the interactions within and between them. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms or are influenced by the effects of human activities in their environment.

Ecosystem-based adaptation (EBA): The use of ecosystem management activities to increase the resilience and reduce the vulnerability of people and ecosystems to climate change.

Ecosystem health: The state or condition of an ecosystem in which its dynamic attributes are expressed within the normal ranges of activity relative to its ecological state of development.

Ecosystem services: Goods and services provided by ecosystems, as an intrinsic property of its functionality, to humans.

Endocrine disruptors: Chemicals that can interfere with endocrine (or hormonal) systems and sometimes also referred to as hormonally active agents, endocrine disrupting chemicals, or endocrine disrupting compounds.

Energy mix: Various primary energy sources used in a given geographic region.

Energy security: The uninterrupted availability of energy sources at an affordable price.

Emission scenario: A plausible representation of the future development of emissions of substances that are radiatively active (e.g. greenhouse gases (GHGs) or aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change, energy and land use) and their key relationships. Concentration scenarios, derived from emission scenarios, are often used as input to a climate model to compute climate projections.

Endemic species: Plants and animals that are only found in one geographic region.

Energy system: The energy system comprises all components related to the production, conversion, delivery and use of energy.

Equity: The principle of being fair and impartial, and a basis for understanding how the impacts and responses to climate change, including costs and benefits, are distributed in and by society in more or less equal ways. Often aligned with ideas of equality, fairness and justice, and applied with respect to equity in the responsibility for, and distribution of, climate impacts and policies across society, generations and gender, and in the sense of who participates and controls the processes of decision-making.

Extensive agriculture: System of crop cultivation using small amounts of labour and capital in relation to the area of land being farmed.

Evaporation: The physical process by which a liquid (e.g. water) becomes a gas (e.g. water vapour).

Evapotranspiration: The combined processes through which water is transferred to the atmosphere from open water and ice surfaces, bare soil, and vegetation that make up the Earth's surface.

Extreme weather event: An event that is rare at a particular place and time of year. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense.

Exposure: The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.

Fertiliser: Any material of natural or synthetic origin that is applied to soil or to plant tissues to supply plant nutrients. Many sources of fertiliser exist, both natural and industrially produced. For most modern agricultural practices, fertilisation focuses on three main macronutrients: nitrogen (N), phosphorus (P), and potassium (K) with occasional addition of supplements like rock flour for micronutrients.

Flood: The overflowing of the normal confines of a stream or other water body, or the accumulation of water over areas that are not normally submerged. Floods can be caused by unusually heavy rain, for example during storms and cyclones.

Food security: The state of having reliable access to a sufficient quantity of safe, affordable and nutritious food that meets people's dietary needs and food preferences for an active and healthy life. Six pillars determine food security: food availability, food access, food use, food stability, agency and sustainability.

Food system: All the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socio-economic and environmental outcomes.

Food web: Complex network of interconnecting and overlapping food chains showing feeding relationships within a community.

Fossil fuels: Carbon-based fuels from fossil hydrocarbon deposits, including coal, oil, and natural gas.

Global Horizontal Irradiance (GHI): The amount of terrestrial irradiance falling on a surface horizontal to the surface of the earth.

Global change: A generic term to describe global-scale changes in systems, including the climate system, ecosystems and social-ecological systems.

Global warming: The estimated increase in global mean surface temperature (GMST) averaged over a 30-year period, or the 30-year period centred on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified.

Governance: The structures, processes, and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local.

Greenhouse gas (GHG): Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds. This property causes the greenhouse effect.

Gross domestic product (GDP): The standard measure of the value added created through the production of goods and services in a country during a certain period.

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

Heat stress: A range of conditions in, for example, terrestrial or aquatic organisms when the body absorbs excess heat during overexposure to high air or water temperatures or thermal radiation.

Heat wave: Prolonged period of excessively high temperatures, often accompanied by high humidity, that poses significant health risks and impacts the environment. The exact criteria for a heat wave can vary based on regional climate conditions, but it generally involves temperatures significantly above the average for a specific area and duration.

Heavy metals: Group of metals and metalloids that have relatively high density and are toxic even at ppb (parts per billion) levels.

Hydroelectricity (or hydroelectric power): Electricity generated from hydropower (water power).

Hydropower: Power harnessed from the flow of water.

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

Incremental adaptation: Adaptation that maintains the essence and integrity of a system or process at a given scale. Incremental adaptations to change in climate are understood as extensions of actions and behaviours that already reduce the losses or enhance the benefits of natural variations in extreme weather/climate events.

Indirect driver: Factor that alter and influence direct drivers, as well as other indirect drivers.

Industrial agriculture: Intensive farming of live animals and crops for the mass production of food and food byproducts treated as commodities.

Inequality: Uneven opportunities and social positions, and processes of dis- crimination within a group or society, based on gender, class, ethnicity, age and (dis)ability, often produced by uneven development. Income inequality refers to gaps between the highest and lowest income earners within a country and between countries.

Intergovernmental Panel on Climate Change (IPCC): The United Nations body for assessing the science related to climate change.

Internet of Things (IoT): The network of computing devices embedded in everyday objects such as cars, phones and computers, connected via the internet, enabling them to send and receive data.

International Atomic Energy Agency (IAEA): Intergovernmental for cooperation in the nuclear field and seeks to promote the safe, secure and peaceful use of nuclear technologies.

Jessour (singular jesr): Water-harvesting system in Tunisia composed of earth and dry stone structures. A kind of small dam placed in ravines and wadis, they limit the rapid flow of rainwater and direct it towards retention areas.

Land Cover (LC): The surface components of land that are physically present and visible, being either vegetation, naked areas or anthropogenic constructions.

Land cover change: Change from one land cover class to another, due to change in land use or change in natural conditions

Land degradation: A negative trend in land condition, caused by direct or indirect human-induced processes including anthropogenic climate change, expressed as a long-term reduction or loss of at least one of the following: biological productivity, ecological integrity or value to humans.

Land management: The sum of land-use practices (e.g. sowing, fertilising, weeding, harvesting, thinning and clear-cutting) that take place within broader land-use categories.

Land Use (LU): It corresponds to the socio-economic description (functional dimension) of areas.

Land Use Change (LUC): The change from one land use category to another.

Lifecycle assessment (LCA): Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product or service throughout its lifecycle.

Lifestyle changes: Deliberate modification of personal habits and behaviours with the goal of improving one's physical, mental, or social well-being. These changes can involve adjustments in various aspects of life, such as diet, exercise, sleep patterns, stress management, or environmental sustainability practices. The intent is often long-term, aiming to improve health outcomes, enhance quality of life, or align with certain values, such as reducing one's carbon footprint.

Livelihood: The resources used and the activities undertaken in order for people to live. Livelihoods are usually determined by the entitlements and assets to which people have access. Such assets can be categorised as human, social, natural, physical or financial.

Maladaptation (Maladaptive actions): Actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas (GHG) emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence.

Malnutrition: Deficiencies, excesses, or imbalances in a person's intake of energy and/or nutrients. The term malnutrition addresses three broad groups of conditions: undernutrition, which includes wasting (low weight-for-height), stunting (low height-for-age), and underweight (low weight-for-age); micronutrient-related malnutrition, which includes micronutrient deficiencies (a lack of important vitamins and minerals) or micronutrient excess; and overweight, obesity and diet-related non-communicable diseases (such as heart disease, stroke, diabetes and some cancers). Micronutrient deficiencies are sometimes termed 'hidden hunger' to emphasise that people can suffer from malnutrition due to a lack of essential nutrients, even when their caloric intake is sufficient. Hidden hunger can apply even where people are obese.

Manure: Organic matter, primarily composed of animal faeces and urine, that is used as a natural fertiliser in agriculture to enrich the soil with essential nutrients. It can also include plant matter such as straw, which is used to absorb animal waste. Manure provides nitrogen, phosphorus, potassium, and other nutrients that help improve soil structure, water retention, and the overall fertility of the land, promoting plant growth.

Mediterranean Basin: In this report, a simple regular latitude-longitude box structures of Mediterranean landscapes are (29°N to 47.5°N and 10°W to 39°E), which includes some regions with non-Mediterranean climates, such as the Alps, the Eastern Balkans or part of the Sahara. This definition of the Mediterranean region is similar to the MED zone adopted in IPCC-AR6 (IPCC, 2021) and MAR1 (MedECC, 2020).

Mediterranean diet: Dietary pattern inspired by the traditional eating habits of people living in countries bordering the Mediterranean Sea. It is widely recognized for its health benefits and has been linked to improved cardiovascular health, longevity, and a lower risk of chronic diseases. It is characterised by high consumption of plant-based foods, healthy fats (e.g. olive oil), moderate intake of fish and poultry, low consumption of red meat, sweets and dairy products and wine in moderation.

Meskat: A traditional water-harvesting system adapted especially to the Tunisian Sahel. It is presented in the form of an impluvium that intercepts runoff water and channels it towards a series of well-defined basins.

Mgoud: floodwater harvesting and spreading or spate irrigation using diversion dykes.

Middle East and North Africa (MENA): Region that covers the enormous area extending from the Atlantic coast of Africa to the borders of Pakistan and Afghanistan in Central Asia and from the Mediterranean littoral to the southern boundaries of the Sahara Desert.

Migration (of humans): Movement of a person or a group of persons, either across an international border, or within a State. It is a population movement, encompassing any kind of movement of people, whatever its length, composition and causes; it includes migration of refugees, displaced persons, economic migrants, and persons moving for other purposes, including family reunification.

Mitigation (of climate change): A human intervention to reduce emissions or enhance the sinks of greenhouse gases.

Mitigation measures: In climate policy, mitigation measures are technologies, processes or practices that contribute to mitigation, for example, renewable energy technologies, waste minimisation processes, and public transport commuting practices.

Models: Structured imitations of a system's attributes and mechanisms to mimic the appearance or functioning of systems, for example, the climate, the economy of a country, or a crop. Mathematical models assemble (many) variables and relations (often in a computer code) to simulate system functioning and performance for variations in parameters and inputs.

Modified consumption patterns: Significant changes or adjustments in the way individuals or groups consume goods and services. These changes can occur in various aspects of consumption, such as food, energy, clothing, or other resources, often driven by health, environmental, economic, or ethical concerns. Modifying consumption patterns typically involves adopting more sustainable, efficient, or mindful approaches to using resources, with the aim of reducing waste, minimising environmental impact, or improving personal well-being.

Monogastric: An animal with a single-compartmented stomach, in livestock farming, mainly pigs and poultry.

Nature-based solutions: Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. Examples of NbS are reforestation and afforestation to help sequester carbon and improve biodiversity, wetland restoration to enhance flood control, improve water quality, and provide habitat for wildlife or green Infrastructure to manage stormwater and reduce urban heat.

North Atlantic Oscillation: Climate phenomenon in the North Atlantic Ocean characterised by fluctuations in the atmospheric pressure difference between the Icelandic Low (a low-pressure area near Iceland) and the Azores High (a high-pressure area near the Azores Islands). These fluctuations influence the strength and direction of westerly winds and storm tracks across the North Atlantic region, affecting the weather in Europe, North America, and parts of North Africa.

Ocean acidification: A reduction in the pH of the ocean, accompanied by other chemical changes (primarily in the levels of carbonate and bicarbonate ions), over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide (CO2) from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity.

Organic farming: An agricultural production system that aims to utilise natural processes and cycles to limit off-farm and notably synthetic inputs, while also aiming to enhance agroecosystems and society. Official national or regional labels certify it.

Pandemic: A worldwide outbreak of a disease in humans in numbers clearly in excess of normal.

Pathways: The temporal evolution of natural and/or human systems towards a future state. Pathway concepts range from sets of quantitative and qualitative scenarios or narratives of potential futures to solution-oriented decision-making processes to achieve desirable societal goals. Pathway approaches typically focus on biophysical, techno-economic, and/or socio-behavioural trajectories and involve various dynamics, goals, and actors across different scales.

Persistent organic pollutants (POPs): Toxic chemicals that adversely affect human health and the environment around the world.

Pesticide: A substance used to kill, repel, or control pests. Pesticides may be synthetic chemicals, natural chemicals, or biological agents (such as a virus, bacterium, or fungus). Most pesticides are used as plant protection products (also known as crop protection products), which in general protect plants from weeds, fungi, or insects that are considered to be pests. Along with these benefits, pesticides also have drawbacks, such as potential toxicity to humans and other species.

Photovoltaics (PV): The conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect. The photovoltaic effect is commercially used for electricity generation and as photosensors. A photovoltaic system employs solar modules, each comprising a number of solar cells, which generate electrical power. Photovoltaic technology helps to mitigate climate change because it emits much less carbon dioxide than fossil fuels.

Phytotoxicity: Any adverse effects on plant growth, physiology, or metabolism caused by a chemical substance.

Policies (for climate change mitigation and adaptation): Strategies that enable actions to be undertaken to accelerate adaptation and mitigation. Policies include those developed by national and subnational public agencies, and with the private sector. Policies for adaptation and mitigation often take the form of economic incentives, regulatory instruments, and decision-making and engagement processes.

Poverty: A complex concept with several definitions stemming from different schools of thought. It can refer to material circumstances (such as need, pattern of deprivation or limited resources), economic conditions (such as standard of living, inequality or economic position) and/or social relationships (such as social class, dependency, exclusion, lack of basic security or lack of entitlement).

Qanat system: A system for transporting water from an aquifer or well to the surface through an underground aqueduct. The system originated approximately 3000 years ago in Iran. The function is essentially the same across the Middle East and North Africa, but the system operates under a variety of regional names: ***qanat*** in Iran and Malta, ***foggara*** in Algeria, ***falaj*** in Oman and the United Arab Emirates.

Pre-industrial (period): The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial global mean surface temperature (GMST).

Projection: A potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realised.

Reforestation: Reconversion to forest of land that has been forest before being converted to some other use.

Region: Land and/or ocean area characterised by specific geographical and/or climatological features. The climate of a region emerges from a multi-scale combination of its own features, remote influences from other regions, and global climate conditions.

Renewable energy (RE): Any form of energy that is replenished by natural processes at a rate that equals or exceeds its rate of use.

Representative Concentration Pathways (RCPs): Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover. The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasises that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome. RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which integrated assessment models produced corresponding emission scenarios. Extended concentration pathways describe extensions of the RCPs from 2100 to 2300 that were calculated using simple rules generated by stakeholder consultations, and do not represent fully consistent scenarios. Four RCPs, produced from integrated assessment models, span a range from approximately below 2°C warming to high (>4°C) warming best-estimates by the end of the 21st century: RCP2.6, RCP4.5 and RCP6.0 and RCP8.5.

RCP2.6: One pathway where radiative forcing peaks at approximately 3 W m^{-2} and then declines to be limited at 2.6 W m^{-2} in 2100 (the corresponding Extended Concentration Pathway, or ECP, has constant emissions after 2100).

RCP4.5 and RCP6.0: Two intermediate stabilisation pathways in which radiative forcing is limited at approximately 4.5 W m^{-2} and 6.0 W m^{-2} in 2100 (the corresponding ECPs have constant concentrations after 2150).

RCP8.5: One high pathway which leads to >8.5 W m^{-2} in 2100 (the corresponding ECP has constant emissions after 2100 until 2150 and constant concentrations after 2250).

Resilience: The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation.

Restoration: In environmental context, restoration involves human interventions to assist the recovery of an ecosystem that has been previously degraded, damaged or destroyed.

Risk: The potential for adverse consequences. In the context of climate change, risks can arise from potential impacts of extreme weather events or unfavourable climate trends. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.

Runoff: The flow of water over the surface or through the subsurface, which typically originates from the part of liquid precipitation and/or snow/ice melt that does not evaporate or refreeze, and is not transpired.

Saltwater intrusion: process by which saltwater from the ocean infiltrates freshwater aquifers, rivers, or coastal ecosystems. This phenomenon typically occurs in coastal areas where freshwater and saltwater are in close proximity, and it is often driven by human activities or environmental factors that disturb the natural balance between these two water sources..

Scenario: A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g. rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.

Semi-arid zone: Areas where vegetation growth is constrained by limited water availability, often with short growing seasons and high interannual variation in primary production. Annual precipitation ranges from 300 to 800 mm, depending on the occurrence of summer and winter rains.

Soil erosion: The displacement of the soil by the action of water or wind. Soil erosion is a major process of land degradation.

Soil moisture: Water stored in the soil in liquid or frozen form. Root-zone soil moisture is of most relevance for plant activity.

Soil organic matter: The organic component of soil, comprising plant and animal residue at various stages of decomposition, and soil organisms.

Solar energy: Energy from the Sun. Often the phrase is used to mean energy that is captured from solar radiation either as heat, as light that is converted into chemical energy by natural or artificial photosynthesis, or by photovoltaic panels and converted directly into electricity.

SRES: Emissions scenarios and storylines of the 'Special Report on Emissions Scenarios' of the IPCC (Nakićenović et al., 2000)

A1: a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies

A2: a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines

B1: a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies

B2: a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

Streamflow: Water flow within a river channel, for example, expressed in $m^3 s^{-1}$. A synonym for river discharge.

Sustainability: A dynamic process that guarantees the persistence of natural and human systems in an equitable manner.

Sustainable Development Goals (SDGs): The 17 global goals for development for all countries established by the United Nations through a participatory process and approved in 2015. They are elaborated in the 2030 Agenda for Sustainable Development, including ending poverty (SDG 1) and hunger (SDG 2); ensuring health and well-being (SDG 3), education (SDG 4), gender equality (SDG 5), clean water (SDG 6) and energy (SDG 7), and decent work (SDG 8); building and ensuring resilient and sustainable infrastructure (SDG 9), cities (SDG 10) and consumption (SDG 11); reducing inequalities (SDG 12); protecting land (SDG 15) and water (SDG 14) ecosystems; promoting peace, justice, strong institutions (SDG 16) and partnership (SDG 17); and taking urgent action on climate change (SDG 13).

Synthetic fertiliser: Synthetically derived fertilisers manufactured from minerals, gases from the air and inorganic waste materials.

Trade-off: A competition between different alternatives. In policy context, a trade-off exists when one of the objectives of the intervention (e.g. reducing greenhouse gas emissions) reduces the likelihood of achieving another objective (e.g. biodiversity conservation, energy security).

Transformation: A change in the fundamental attributes of natural and human systems.

Transformational adaptation: Adaptation that changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts.

Transition: The process of changing from one state or condition to another in a given period of time. Transition can occur in individuals, firms, cities, regions and nations, and can be based on incremental or transformative change.

Urbanisation: A multi-dimensional process that involves at least three simultaneous changes: (1) land-use change: transformation of formerly rural settlements or natural land into urban settlements; (2) demographic change: a shift in the spatial distribution of a population from rural to urban areas; and (3) infrastructure change: an increase in provision of infrastructure services including electricity, sanitation, etc. Urbanisation often includes changes in lifestyle, culture, and behaviour, and thus alters the demographic, economic, and social structure of both urban and rural areas.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Water footprint: Measure of the total amount of freshwater used directly and indirectly to produce goods and services consumed by an individual, community, or business. It includes all aspects of water consumption, from the water used in growing food to the water involved in manufacturing products. The concept helps assess the environmental impact of water use and guides efforts toward sustainable management of water resources. There are three types of Water Footprints. The blue water footprint refers to the use of surface and groundwater (rivers, lakes, and aquifers) for irrigation, industrial processes, or domestic consumption. The green water footprint accounts for the rainwater consumed by crops and plants, especially in agriculture and the grey water footprint represents the amount of freshwater needed to dilute pollutants to maintain water quality standards, reflecting the environmental impact of water pollution..

Water security: The state of having reliable access to a sufficient quantity of clean water.

Well-being: A state of existence that fulfils various human needs, including material living conditions and quality of life, as well as the ability to pursue one's goals, to thrive and to feel satisfied with one's life. Ecosystem well-being refers to the ability of ecosystems to maintain their diversity and quality.

Wetland: Land that is covered or saturated by water for all or part of the year (e.g. peatland).

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Annex II: Acronyms, chemical symbols and scientific unites

%	percent
°C	degree Celsius
$	American dollar
€	euro
AARINENA	Association of Agricultural Research Institutions in the Near East and North Africa
ACSAD	Arab Center for the Studies of Arid Zones and Dry Lands
AMWC	Arab Ministerial Water Council
AOAD	Arab Organisation for Agricultural Development
AR4 - IPCC	Fourth Assessment Report
AR5 - IPCC	Fifth Assessment Report
AR6 - IPCC	Sixth Assessment Report
ARIMNET	Agricultural Research In the Mediterranean Network
AV	Agrivoltaics
BAC	Background Assessment Concentrations
BAT	Best Available Technology
BEP	Best Environmental Practice
BOD_5	Biochemical oxygen demand measured in a water sample during 5 days of incubation at 20°C
C	Carbon
CA	Citizens' assembly
CAMRE	Council of Arab Ministers Responsible for Environment
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regionalised Impact model
CBC	Cross-Border Cooperation
CC	Climate change
CF	Carbon footprint
CFS	Committee on World Food Security
CGE	Computable general equilibrium
CIHEAM	International center for Advanced Mediterranean Agronomic Studies
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
c	centi (10^{-2})
CMI	Center for Mediterranean Integration
CMIP5	5th phase of the Coupled Model Intercomparison Project
CNRS	French National Centre for Scientific Research (Centre National de la Recherche Scientifique)
CO_2	Carbon dioxide
COP	Conference of the Parties
CSP	Concentrated solar power
DNA	Deoxyribonucleic acid
DNI	Direct normal irradiance
e.g.	For example
E3ME	Energy-Environment-Economy Global Macro-Economic
EAC	Environmental Assessment Criteria
EDO	European Drought Observatory
EEA	European Environment Agency
EEAA	Egyptian Environmental Affairs Agency
EF	Ecological footprint, environmental footprint
EFC	Ecological footprint of consumption
EFSA	European Food Safety Authority
EIB	European Investment Bank
ENABEL	Belgian Development Agency (Agence de développement de l'état fédéral belge)
ENI	European Neighbourhood Instrument
ENoLL	European Network of Living Labs
eq	Equivalent
ERAMED NET	Euro-Mediterranean Cooperation through ERANET
ERANET	European Research Area Network
ESCWA	Economic and Social Commission for Western Asia
et al.	And others
ETC/CCA	European Topic Center on Climate Change Adaptation
EU	European Union
EURO-CORDEX	European Coordinated Regional Climate Downscaling Experiment
FAO	Food and Agriculture Organisation
FASRB	Framework Agreement on the Sava River Basin
FOD	First Order Draft
g	Gram
G	Giga (10^3)
GCA	Global Center on Adaptation
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
gha	Global hectares
GHG	Greenhouse gas
GHI	Global horizontal irradiance
GISD	Global Investors for Sustainable Development

GIZ	German Corporation for International Cooperation (Deutsche Gesellschaft für Internationale Zusammenarbeit)
GNP	Gross net product
GSDR	Global Sustainable Development Report
GWP-Med	Global Water Partnership-Mediterranean
h	Hecta (10^2)
ha	Hectar
I	Industrialisation/technologisation
i.e.	That is
IAEA	International Atomic Energy Agency
ICWE	International Conference on Water and the Environment
ICZM	Integrated Coastal Zone Management
IEA	International Energy Agency
IMAGE	Integrated Model to Assess the Global Environment
INRM	Integrated Natural Resource Management
IoT	Internet of Things
IPBES	Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRD	French National Research Institute for Sustainable Development (Institut de Recherche pour le Développement)
IRENA	International Renewable Energy Agency
ISRBC	International Sava River Basin Commission
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
J	Joule
K	Kilo (10^3)
kWh	Kilowatt-hour
l	Liter
LAS	League of Arab States
LC	Land cover
LC	Lifestyle change
LCA	Life cycle assessment
LL	Living labs
LNG	Liquefied natural gas
LU	Land use
LULCC	Land Use and Land Cover Changes
M	Mega (10^6)
m	Meter
m	Milli (10^{-3})
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MAP	Mediterranean Action Plan
MAR1	First Mediterranean Assessment Report
MCSD	Mediterranean Commission on Sustainable Development
ME	Middle East
Med	Mediterranean
MED POL	Programme for the Assessment and Control of Marine Pollution in the Mediterranean
MedECC	Mediterranean Experts on Climate and environmental Change
MENA	Middle East and North Africa
Mtoe	Megatonne of oil equivalent (10^6)
µ	Micro (10^{-6})
n	Nano (10^{-9})
N	Nitrogen
N/A, N.A.	Not applicable
N_2O	Nitrous oxide
NA	North Africa
NAO	North Atlantic Oscillation
NbS	Nature-based Solution
NCoP	Nexus community of practice
NCP	Moroccan National Climate Plan
NDC	Nationally Determined Contribution
NECP	National Energy and Climate Plans
NEXUS-NESS	NEXUS Nature Ecosystem Society Solution
NGO	Non-governmental organisation
no.	Number
NOx	Nitrogen oxides
NSSD	National Strategy for Sustainable Development
NWFE	Nexus of Water, Food and Energy
NWSS	Lebanese National Water Sector Strategy
O_3	Ozone
OECD	Organisation for Economic Co-operation and Development
OME	Mediterranean Energy Observatory (Organisation Méditerranéenne de l'Energie; presently: OMEC, Organisation Méditerranéenne de l'Energie et du Climat)
ONEE	Moroccan National Office of Electricity and Drinking Water (Office National de l'Electricité et de l'Eau Potable)
P	Peta (10^{15})
P	Population
P3	Public-Private Partnerships
PACE	Parliamentary Assembly of the Council of Europe

PACTE	Programme for Adaptation to Climate Change in Vulnerable Rural Territories of Tunisia
PFAS	per- and polyfluoroalkyl substances
PG	Population growth
PM2.5	Fine particulate matter (with diameter below 2.5 µm)
PNAEDD	Algerian National Action Plan for the Environment and Sustainable Development
PNE	Moroccan National Water Plan
PNRC	Moroccan National Plan Against Global Warming
POP	Persistent organic compound
PRB	Population Reference Bureau
PRIMA	Partnership for Research and Innovation in the Mediterranean Area
PV	Photovoltaic
RBMP	River Basin Management Plan
RCP	Representative Concentration Pathway
REDD+	Reducing emissions from deforestation and forest degradation in developing countries. The '+' stands for additional forest-related activities that protect the climate, namely sustainable management of forests and the conservation and enhancement of forest carbon stocks.
REN21	Renewable Energy Policy Network for the 21st Century
RIH	Regional Innovation Hub
RVA	Risk and Vulnerability Analysis
SDG	Sustainable Development Goals
SDSN	Sustainable Development Solutions Network
SEI	Stockholm Environment Institute
SG	Serious games
SIDA	Swedish International Development Cooperation Agency
SIM4NEXUS	Sustainable Integrated Management FOR the NEXUS of water-land-food-energy-climate for a resource-efficient Europe
SNEDD	Algerian National Strategy for the Environment and Sustainable Development
SNGID	National Strategy for Integrated Waste Management (Algeria)
SNRCC	Tunisian National Plan for Adaptation to Climate Change and Strategy for Resilient Development
SO_2	Sulfur dioxide
SPANB	Algerian Strategy and National Action Plan for Biodiversity
SPI	Science-Policy Interface
SPM	Summary for Policymakers
sq	Square
SRES	Special Report on Emissions Scenarios
SST	Sea surface temperature
STEG	Tunisian Company of Electricity and Gas (Société Tunisienne de l'Électricité et du Gaz)
t	Tonne
T	Tera (10^{12})
U	Urbanisation
UfM	Union for the Mediterranean
UfM CCEG	Union for the Mediterranean Climate Change Expert Group
UN	United Nations
UN DESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations Children's Fund, originally known as the United Nations International Children's Emergency Fund
UNU	United Nations University
UNWTO	United Nation World Tourism Organisation
US	United States
USAID	United States Agency for International Development
VOC	Volatile organic compound
W	Watt
W	War
WEF	Water-Energy-Food
WEFE	Water-Energy-Food-Ecosystems
WEN	Water-Energy Nexus
WF	Water footprint
WG ENV-CC	Working Group on Environment and Climate Change
WHO	World Health Organisation
WMO	World Meteorological Organisation
WRG	Water Resources Group
ww	Wet weight
y, yr	Year
ZOD	Zero Order Draft

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