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Nexus approach to enhance water-energy-food security and ecosystems resilience under climate change in the Mediterranean

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The Mediterranean Basin, already a water-scarcity hotspot, faces intensifying droughts and warming that strain the water–energy–food–ecosystems (WEFE) nexus. Climate impacts cascade across sectors, while siloed responses risk maladaptation. Nexus-based solutions—centred on water—can foster synergies and reduce trade-offs, with nature-based, socially inclusive, and clean energy strategies offering transformative potential. Yet governance, cooperation, and data gaps persist; closing these is vital to operationalize the nexus and advance regional sustainability.

The Mediterranean basin has long demonstrated resilience to harsh environmental challenges, including arid, hot climates and nutrient-poor soils. These conditions have shaped its land- and sea-scapes and fostered agricultural, fisheries and water management practices refined over millennia[1]. However, recent IPCC (Intergovernemental Panel on Climate Change) and MedECC (Mediterranean Experts on Climate and environmental Change) reports underscore that the region is warming 20% faster than the global average, altering rainfall patterns and accelerating sea-level rise, all meeting increasingly fragile socio-economic systems[2–4]. This alarming trajectory confirms the Mediterranean as a 'climate change hotspot'[5], with escalating climate hazards compounded by high vulnerability and exposure[4]. Among these, drought emerges as the primary and most wide-spread risk factor, driven by rising evaporative demand and declining precipitation[6–8]. The latest IPCC report and subsequent attribution studies confirm that climate change is increasing the frequency and severity of agricultural and hydrological droughts in the Mediterranean[9,10]. Moreover, confidence in human influence contributing to the severity of these events is highest—at a medium confidence level—specifically in Mediterranean climates, as defined by the Köppen climate classification, which includes the Mediterranean region and western North America[11]. These increasingly arid conditions exacerbate water scarcity, threatening agriculture, ecosystems, and, to some extent, energy systems[3,12,13]. Water scarcity, the main challenge identified in the Mediterranean region, both as a long-standing structural issue and as a pressure intensified by climate change, is deeply interconnected with the socio-economic vulnerabilities of the basin. This unsustainability manifests not only through pervasive insecurity but also through pronounced regional disparities with stronger resource limitations in the South and East of the basin. The intricate interdependencies between water, energy, food and ecosystems (WEFE) further compound these challenges, emphasizing the urgent need for integrated and equitable solutions, as responses aiming to address challenges linked to one component in isolation may start a series of cascading effects on the other components of WEFE[14]. Climate change, but also other direct (e.g. pollution, land use changes) and indirect (e.g. lifestyle changes, population growth, conflict) drivers of change, exacerbate these linkages, heightening the risks of water scarcity and resource mismanagement, which pose critical threats to the region's resilience and sustainability[15]. For this reason, responses to safeguard the water-scarce region's future should follow a nexus approach to increase the synergies among WEFE components interactions and reduce potential trade-offs leading to maladaptation, and to promote integrated solutions that optimize co-benefits across different sectors. For instance, in the context of water scarcity, unsustainable irrigation practices have caused heightened soil salinity and extensive land degradation in certain areas[1,16] further exacerbating water and food insecurity and reducing ecosystems health. These outcomes result from adaptation strategies narrowly focused on singular short-term goals, such as maximizing food production through intensive agriculture, often at the cost of water availability, soil health, and biodiversity. For example, Morocco's solar-powered irrigation systems have improved agricultural water efficiency, but when deployed without governance oversight, they risk

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accelerating aquifer depletion[17]. In Sicily, the expansion of tropical crops like mangoes reflects adaptation, but also raises concerns over ecosystem transformation[18]. These trends reflect a fundamental tension: while short-term sectoral responses may seem effective in isolation, they often deepen interlinked vulnerabilities by neglecting systemic feedbacks. Technological fixes, for instance, may increase efficiency but fall short without behavioural change, institutional coordination, and supportive policy frameworks. A notable example is the large-scale irrigation modernization programme carried out in Spain between 2002 and 2015, one of the most extensive globally. While its primary objective was to increase application efficiency, analyses have shown that it did not result in actual water savings. Instead, it led to a rebound effect, where improved efficiency paradoxically encouraged greater water use[19,20]. This case highlights that technology adoption must be accompanied by complementary measures such as robust water accounting systems and appropriate allocation frameworks. Similarly, other Mediterranean experiences underline that innovation without governance may foster maladaptation. For instance, the expansion of solar-powered groundwater pumping in the Kebili Region (Tunisia) provided new opportunities for farmers but also contributed to groundwater depletion when introduced without regulatory safeguards[14]. Another case is wastewater reuse: widely practiced in the southern Mediterranean, it remains constrained by weak governance and fragmented legislation, limiting its potential as a safe and sustainable nexus solution[14]. These examples demonstrate that technological advances in the region can only deliver long-term benefits when embedded within coherent governance and institutional frameworks. This underscores the need to transition from fragmented adaptation to an integrated paradigm.

While integrative frameworks, such as Integrated Water Resources Management (IWRM) or Social-Ecological Systems (SES), have been applied to resource challenges, they show important limitations in the Mediterranean context. IWRM, though relevant for water-scarce regions, is predominantly water-centric and typically applied at the river basin scale, which often overlooks broader socio-political dynamics. The SES framework integrates ecological, social, and economic perspectives through systems thinking, but its insights are frequently difficult to operationalize or translate into actionable policy. By contrast, a WEFE nexus approach enables a more comprehensive analysis of the interconnections and interdependencies among water, energy, food systems, and ecosystems, emphasizing policy coherence and integrated resource planning at national and regional scales. This makes it particularly suited to identifying sectoral trade-offs, enhancing synergies and resource efficiency, and reducing the risk of maladaptation. For example, irrigation modernization projects that only addressed water efficiency gains, without considering broader nexus dynamics, have in some cases resulted in rebound effects and unintended pressures on other sectors[14,21].

The objective of this perspective is to assess how climate change intensifies the interlinked challenges of the WEFE nexus in the Mediterranean, with water scarcity as the defining and most pressing issue. We specifically aim to (i) synthesize evidence of how climate change is amplifying drought, variability in water availability, and cascading risks across energy, food, and ecosystems, (ii) examine how these pressures create trade-offs and feedbacks when addressed in isolation, and (iii) highlight nexus-based adaptation and mitigation solutions that place water at their core while fostering synergies, reducing trade-offs, and providing lessons for other water-scarce regions globally. The scope of this article is to synthesize existing knowledge and highlight opportunities for advancing nexus-based solutions, rather than to develop a new quantitative framework. Based on a systematic literature review and expert knowledge, this perspective adopts a structured approach that first outlines the key regional challenges, then examines sectoral WEFE interdependencies, and finally explores nexus-based solutions for adaptation and resilience. However, we complement our synthesis by drawing on existing analytical case studies in the Mediterranean that employ quantitative approaches (e.g. assessments of irrigation modernization or agrivoltaics deployment in Spain, expansion of solar-powered groundwater pumping in Tunisia, rebound effects of water efficiency interventions, resilience analyses through a WEFE nexus lens in Lebanon, …). These examples demonstrate how quantitative evidence supports the insights discussed here and illustrate the potential for integrating case-based analysis with broader nexus perspectives. By integrating a ripple-effect framework, we highlight how climate change-driven changes in one sector cascade through others, emphasizing the need for holistic, cross-sectoral policymaking to help frame resilience, as illustrated for instance for Lebanon[22].

Cascading effects of climate change and associated responses on water, energy and food security, and ecosystem health

The concept of cascading effects forms the crux of understanding how interconnected the WEFE components truly are in the Mediterranean region. This perspective highlights that no component—water, energy, food, or ecosystems—exists in isolation; rather, they are woven into a complex and dynamic web where changes in one domain reverberate through the others. Climate change, as a dominant direct driving force, acts as a catalyst that magnifies these interactions (Fig. 1, left-hand side).

Interconnected water, energy, food security and ecosystems health challenges in the Mediterranean

In the water-scarce Mediterranean region, the interconnections between water, energy, food security, and ecosystem health are particularly intricate, forming dynamic feedback loops and trade-offs that deeply influence the region's sustainability and resilience. Water scarcity, already a defining feature of the Mediterranean climate, is exacerbated by climate change, while water plays a central role not only in sustaining ecosystems but also in supporting agricultural production, energy generation, and human well-being[3]. It is fundamental to maintaining healthy ecosystems, reducing disease burdens, promoting gender equity, and enhancing both social welfare and economic productivity. Moreover, water is pivotal in climate change adaptation and peacebuilding, acting as a vital connector between the climate system, human society, and the environment[23].

However, warming and rainfall patterns change result in increased freshwater shortages and desertification throughout the basin[24–27]. 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[28]. Water scarcity, driven by reduced rainfall and over-extraction, initiates a domino effect and conflicts across all water-dependent sectors (energy, agriculture, tourism, industry, domestic use, as well as biodiversity conservation)[12,13,28,29].

The Mediterranean region's food system is shaped by the traditional Mediterranean diet, which emphasizes seasonal, plant-based foods and local production practices, contributing to relatively low environmental impacts compared to global dietary patterns[30]. This agroecological model promotes biodiversity and resource efficiency, especially in water-scarce conditions typical of the region[31]. However, increasing exposure to extreme events such as droughts and heatwaves threaten traditional crops like olives and grapes[32–35]. These pressures are compounded by structural trade asymmetries: Southern and Eastern Mediterranean countries prioritize domestic food security but also export select crops (e.g., olive oil, citrus), whereas Northern Mediterranean countries are oriented toward export markets[36,37]. These trade dynamics increase the system's exposure to external shocks and uneven vulnerabilities. For instance, Lebanon's vulnerability to simultaneous climate and economic shocks induce significant risks to the country's ability to maintain a Mediterranean food basket[38] while in the Middle East and North Africa, food trade impacts water, food, and land security as trade-offs across sectors can exacerbate vulnerabilities under conditions of water scarcity and climate stress[39]. Together, these studies underscore how cross-sectoral and cross-border trade dynamics shape the cascading impacts of climate change on Mediterranean food systems. These trends underscore the Mediterranean's dual identity as a model for sustainable diets and a climate-sensitive agricultural zone requiring urgent adaptation strategies. The Mediterranean food system is also entangled in the complex

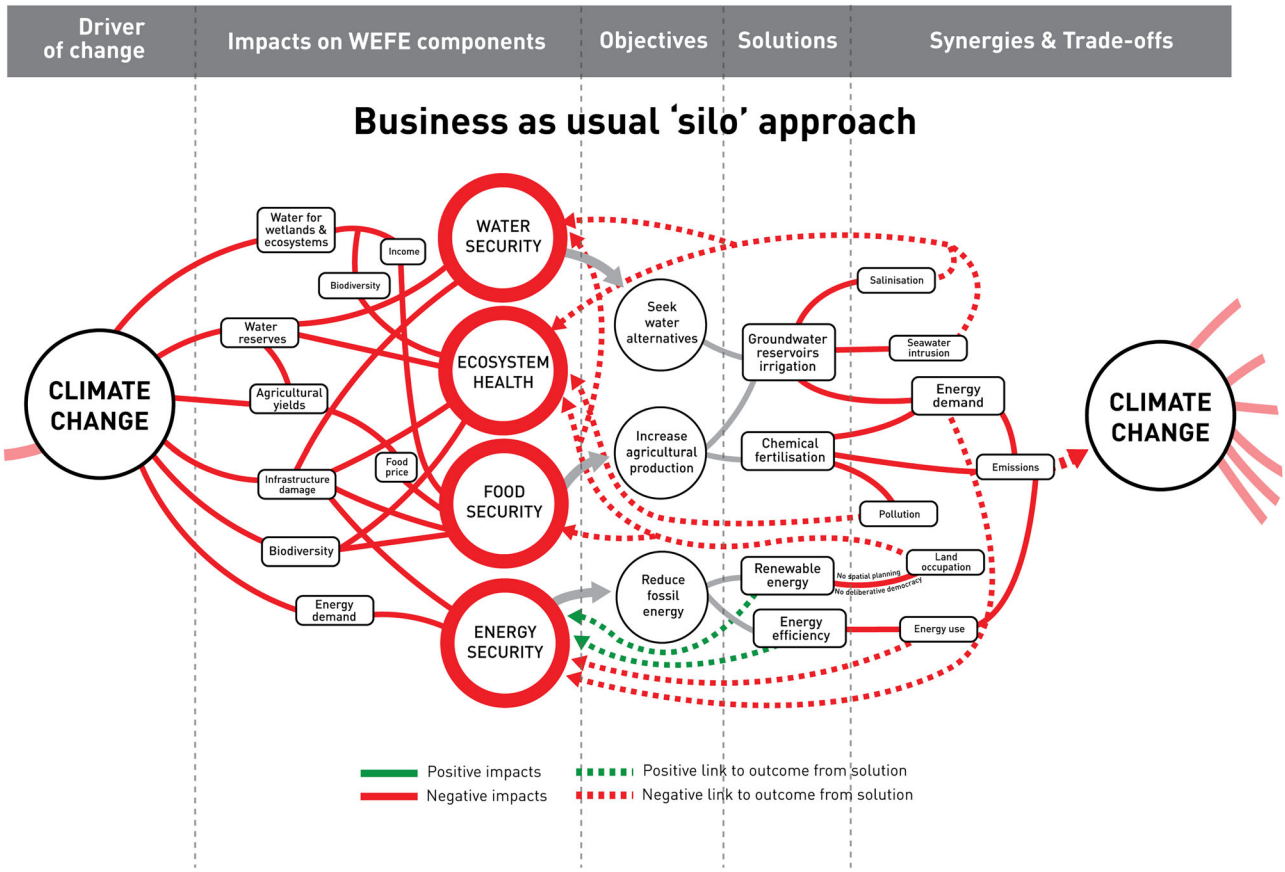

Fig. 1 | Impacts, interactions and cascading effects on the WEFE outcomes of climate change and solutions designed in a sectoral approach. The left-hand side displays the impacts of climate change, on the various processes related to the nexus components and the overall positive or negative effect it has on each nexus component and associated outcomes. The right-hand side displays the various response options for each WEFE component, their different interactions, synergies and trade-offs to the nexus and their eventual positive or negative effect on each WEFE component, and climate change itself. The red (resp. green) arrows display feedbacks deteriorating (resp. improving) a WEFE component or climate trend.

interactions with water, energy, and environmental systems within the WEFE nexus. Climate change, water scarcity and land degradation are projected to cause a 17% decline in agricultural output by 2050, with substantial regional disparities. Lower agricultural yields, caused by drought and heat stress, intensify reliance on irrigation, which again heightens competition for already scarce water resources[12,40]. Rising food prices, a consequence of reduced productivity, place additional stress on energy systems as transportation and processing costs escalate[41]. Vulnerable populations, particularly in North Africa and the Near East, bear the brunt of these interlinked crises, facing not only food insecurity but also socio-economic instability[42].

The Mediterranean region's energy system exhibits distinct characteristics shaped by its geopolitical significance, resource endowments, and socio-economic dynamics. Its strategic location makes it a crucial energy hub between Europe, Africa, and the Middle East, with geopolitical, economic, and environmental challenges shaping its future. The Mediterranean region's energy system is marked by a strong dependence on fossil fuels[13], underpinned by persistent subsidies that hamper progress toward a low-carbon transition[43,44]. Despite the Mediterranean's considerable potential for renewable energy—especially solar and wind—structural challenges remain, including outdated infrastructure, fragmented markets, and limited cross-border coordination[13,45]. These barriers hinder the region's ability to capitalize on its natural advantages. Achieving a successful energy transition in the Mediterranean will require integrated regional planning, infrastructure investments, and policy harmonization to fully exploit renewable resources and enhance long-term energy security[13,45,46]. The Mediterranean region's energy system, while positioned as a solution to mitigate climate change through the provisioning of renewable energy, also contribute to the cascading effects. Hydropower generation potential suffers under diminished water flow, prompting a shift toward thermal or renewable energy sources[13]. The land-use demands of renewable energy farms or biofuel crops create conflicts with food production and the necessary conservation or restoration of ecosystems[47,48].

As for the ecosystems in the Mediterranean basin, climate change exacerbates existing environmental vulnerabilities by increasing the frequency and intensity of wildfires and facilitating the spread of non-indigenous species. These changes threaten the region's rich but fragile ecosystems and biodiversity, with cascading effects on key socio-economic sectors such as fisheries, agriculture, and tourism—pillars of Mediterranean livelihoods[49,50]. The resulting strain on natural resources contributes to growing water, energy, and food insecurity[49], reinforcing the region's status as a climate hotspot.

In sum, climate-driven disruptions to one component of the water–energy–food–ecosystems (WEFE) nexus often trigger ripple effects across others. For example, declining water availability due to droughts and rising temperatures affects agricultural yields and the energy required for irrigation[40]. In this highly interconnected and resource-stressed region, addressing the compounded effects of climate change on all WEFE dimensions requires tailored, integrated adaptation strategies that reflect the Mediterranean's unique ecological and socio-economic context[51].

Adaptation solutions requiring adjustment in natural or human systems in response to the actual and expected climate change and its effects, are needed to moderate harm or exploits beneficial opportunities.

Short-term sectoral and adaptation solutions

To address the challenges in water–scarce regions like the Mediterranean Basin adaptation measures are often designed in silo. However, sectoral adaptation solutions can degrade even more the nexus components and generate feedback loops with the drivers of change, here climate change, for instance resulting in increased greenhouse gas emissions and reduced adaptation capacity in the longer term (Fig. 1, right-hand side).

In the case of water, the reduction in water tables may lead to responses focused on pumping ground water for drinking or irrigation that require energy, can increase salinization and seawater intrusion, which ultimately degrade water quality[52]. The high energy requirements for pumping water drive up costs and, when insufficient renewable energies are available, greenhouse gas emissions. Simultaneously, ecosystems that depend on stable water levels—like wetlands and riparian zones—deteriorate, reducing their capacity to provide critical services such as carbon sequestration, water purification, and flood control. The degradation of these ecosystems, in turn, destabilizes soil quality and local microclimates, further compounding water stress.

Enhancing food production through conventional intensive agriculture requires synthetic fertilizers which production is highly energy intensive, with negative impacts on both climate change and energy security, through increased greenhouse gas emissions and energy demand[53,54]. Also, chemical fertilization risks polluting water with high nitrogen loads, impacting negatively ecosystem's health and food security[55]. Where irrigation needs are satisfied through groundwater, the cascading effects described above are also added.

Photovoltaic and wind-based renewable energy adoption to phase-out fossil fuels requires land which can lead to conflict with other usage such as agriculture, leading to lower food security and ecosystem's health[56,57]. Energy efficiency improvement, if not accompanied by measures promoting energy sufficiency, can result in rebound effects, leading to an increase in energy demand and negative impact on energy security and climate change. These cascading effects interact across scales, and applying sectoral adaptation measures creates feedback loops that amplify the original stressors.

Favouring synergies in the cascade with a nexus approach

In the Mediterranean region, water scarcity is a defining and intensifying challenge. Most studies place water at the core of the nexus-oriented approaches in the region, reflecting the Mediterranean's chronic water scarcity and the strong interdependence of water with energy and food production[58]. Implementing an integrated nexus model that places water at its core in the Mediterranean basin can help mitigate trade-offs among sectors, enhance climate adaptation strategies, and promote sustainable development through region-specific policy actions and technological and social innovation[58–60]. Promoting synergies among the WEFE components and the drivers of change requires innovative, comprehensive, and context-sensitive interventions using a nexus approach. A fundamental shift from sectoral approaches that address water, energy, food, and ecosystems independently, to measures recognizing the interconnected nature of these systems and policies that consider their complex interactions, is essential. Several organisations, like the European Union, the World Bank, the International Union for Conservation of Nature (IUCN) and the International Water Association, the USAID, among others, have launched initiatives to build mechanisms for supporting the WEFE nexus approach at various levels[61]. Several adaptation options implemented in the Mediterranean region have been identified that address at least two components of the WEFE and later evaluated them from a nexus perspective[58].

Nexus based solutions implemented in the Mediterranean for integrated resource use

Building resilience across the WEFE components starts with investing in adaptive technologies and sustainable practices and behaviours that can deliver nexus outcomes. The review of those solutions and practices in the Mediterranean (see Methodoloy section and Supplementary note for their selection and processing), show at territorial level, both ecosystem-based[62,63] and technological solutions have been implemented locally for more integrated and efficient resource use[64–67] (Fig. 2a). These solutions, addressing at least 2 components of the WEFE, have been implemented accros the Mediterranean basin with a clear North-South divide (Fig. 2b). However, not all implemented solutions are documented in scientific articles or reports, so the map is necessarily incomplete.

A number of WEFE-solutions support the food system sustainability while minimizing water and energy demand[68–72]. They include both new irrigation techniques and the recovery of traditional ones; the use of renewable energy in agriculture, agrivoltaics without land competition or bio-energy crop production in marginal areas or for self-consumption in agriculture; the use of reclaimed water or desalinated water; or agroecological practices, such as agroforestry, intercropping and cover crops[48,65,73]. A large fraction of water is currently used for cooling thermal power plants, so more efficient cooling technologies are critical for the water-energy supply-demand balance[21,74]. Switching to renewable energies in the Mediterranean also benefits the water, ecosystem, food and energy pillars so that implementation does not involve land competition and resource degradation[64,65,75,76]. Finally, the WEFE nexus allows to better distinguish potential synergies or conflicts between sectoral policies because it provides a framework in which the role of ecosystem services are more explicit[77]. Consumption-oriented solutions, such as returning to a more Mediterranean diet (and its subsequent reduction in meat consumption) and, in general, less wasteful consumption, have high potential for adaptation and mitigation with benefits in all WEFE components[78,79]. Finally, early warning tools and climate services, have also shown broad applicability across various sectors in the Mediterranean[80]. The combination of nexus approaches with climate service studies in the Mediterranean have contributed to the assessment of cross-sectoral impacts of hydro-climatic and socio-economic futures on water resources, habitat for species and food and energy production[67,81–83].

In analysing the relevance of the identified solutions from a nexus perspective, we find that options related to water use and management are the most complex and controversial, because they must account for benefits and trade-offs across multiple WEFE components, rather than focusing narrowly on a single sector. The literature collected from Mediterranean case studies shows that only a few measures can be regarded as consistently "positive" across all four nexus dimensions, which limits their transformative potential (Fig. 2a). On the contrary, social options based on behavioural change show the highest positive effect on all the four components of the nexus, with a robust amount of evidence, and are therefore the most transformative[84–89]. These approaches, which include shifts in consumption patterns, sustainable resource use, and community-driven initiatives, not only reduce environmental pressures but also foster long-term resilience by reshaping societal norms and promoting more sustainable lifestyles. More evidence is needed to assess specific ecosystem-based solutions although currently available studies indicate that nature-based solutions and agroecological management have positive impacts on the four WEFE components. Finally, more evidence is needed to assess the effect of adaptation options related to governance and institutions, in particular on policies on water pricing and limiting, or better managing water use[90,91]. It is important to note that the scientific literature remains unequally distributed across the Mediterranean. Southern and Eastern countries, in particular, face underrepresentation, partly due to limited research funding and language barriers. Many locally implemented solutions—especially indigenous or informal practices—are underreported, highlighting the need for more inclusive and regionally balanced documentation. For example, traditional canalization systems used for date cultivation in the Atlas oases of Morocco have been implemented for millennia to optimize food production while also improving water quality and distribution without requiring energy inputs. However, such practices are scarcely analysed in the international literature and remain absent from peer-reviewed references. This reflects a broader challenge: locally implemented solutions are poorly comparable across countries due to the lack of harmonized and easily accessible

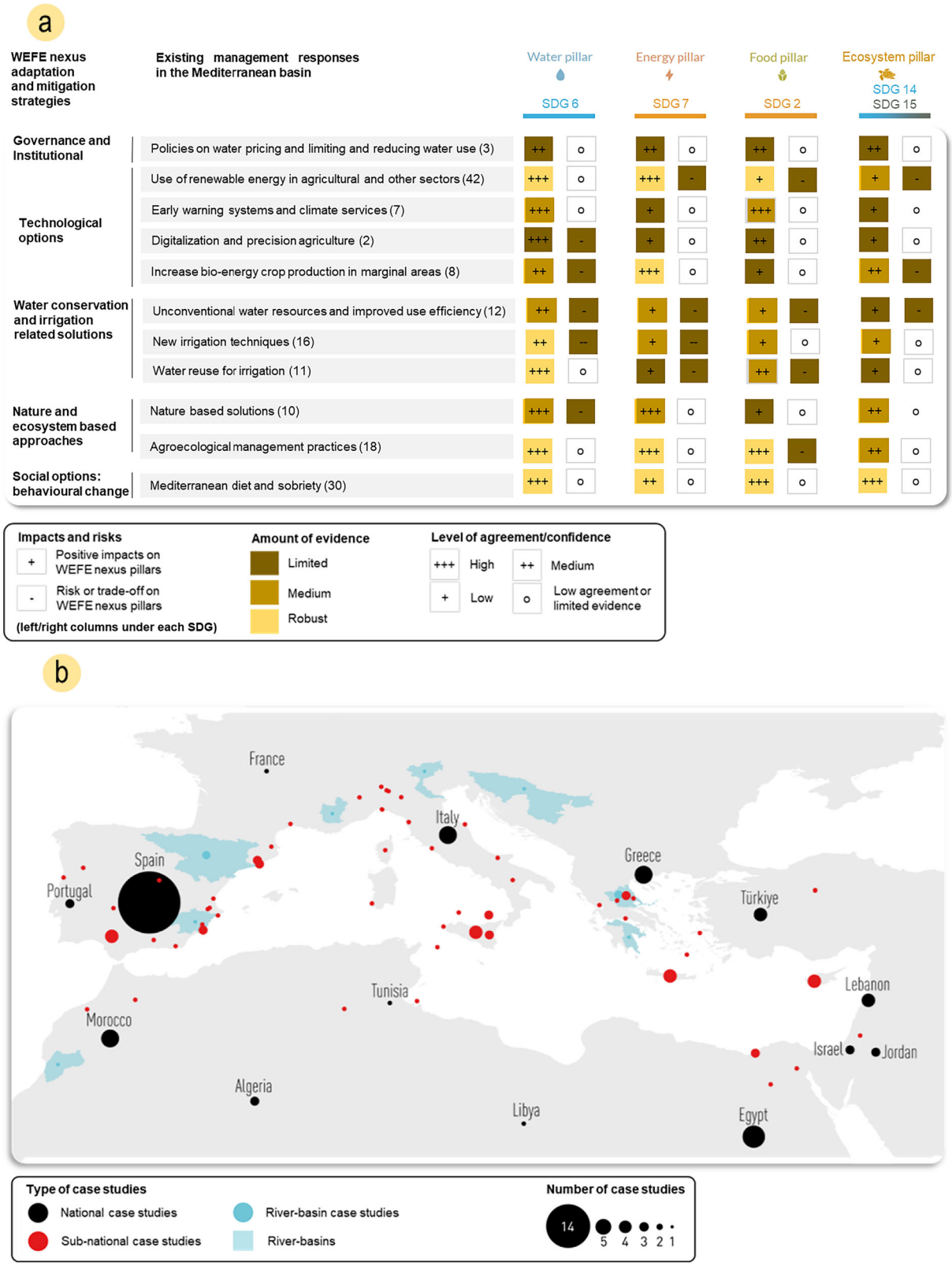

Fig. 2 | Impacts and distribution of implemented WEFE nexus solutions in Mediterranean countries. a Assessment of the main impacts and trade-offs of WEFE nexus adaptation and mitigation solutions implemented in the Mediterranean countries. The link is made to the SDGs through the nexus pillars. Each pillar has two columns indicating positive impacts (left) and risks or trade-offs (right) associated with the solution. The amount of evidence is quantified by the number of articles used (in brackets) for assessing each solution, and categorised by robustness: limited, medium, or robust (shades of brown). Four degrees of agreement measures the consensus between the articles. This figure does not review all possible solutions, but those implemented in the Mediterranean, reported in the scientific literature, and assessed in this study. **b** Spatial distribution of implemented WEFE nexus solutions based on a review of 205 articles (see Supplementary note). Selected solutions address at least 2 of the 4 WEFE components.

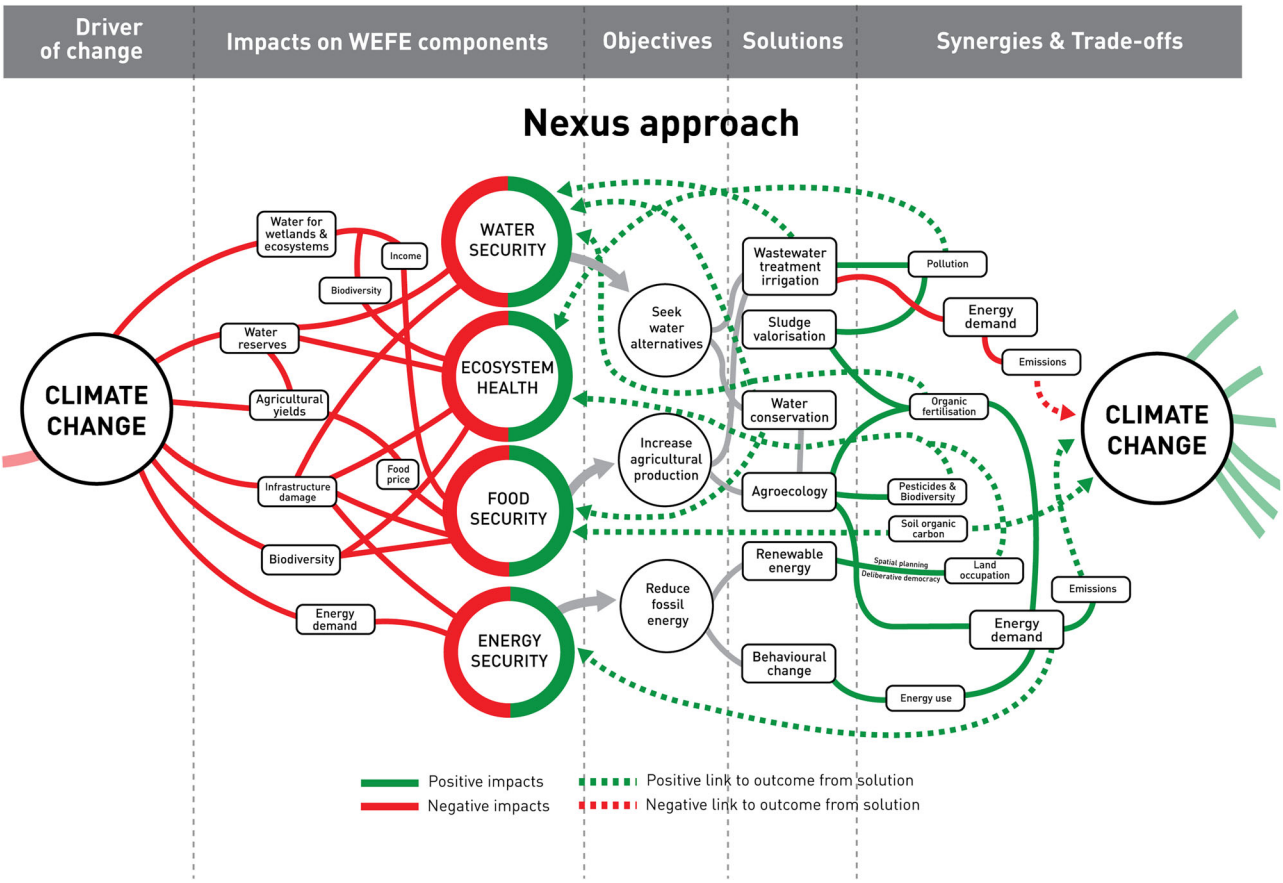

Fig. 3 | Same as Fig. 1 for solutions designed in a nexus approach.

documentation, which is often confined to regional or municipal sources. Beyond these considerations, collaborative pools of experts convened through the MedECC process, or other existing initiatives such as the PRIMA (Partnership for Research and Innovation in the Mediterranean Area) program represent a potential asset for advancing nexus approaches in the region. This scientific network and community of practice can strengthen dialogue, cooperation, and policy coherence across countries, and help foster widely acceptable and transnationally applicable WEFE solutions.

Impact of nexus-based solutions on the cascading effects of climate change on WEFE components

Climate change can affect the effectiveness of adaptation and mitigation measures at various temporal and spatial scales. When solutions are developed in a holistic or a nexus approach, which take into consideration the interactions shown before, more synergies and less trade-offs can lead to mitigating feedback loops that may reverse the negative trends caused by climate change on all WEFE components (Fig. 3, right-hand side). Wastewater treatment, sludge valorization, water conservation, agroecology and consumption changes have successfully been implemented in the Mediterranean with positive cascading effects on the WEFE components (Fig. 2a). Irrigation with treated wastewater favours the valorization of sludge, they both reduce pollution by minimising the the use of synthetic fertilisers and treating polluted water, promoting not only water security, but also ecosystem health[92,93]. Sludge, used as organic fertiliser, also increases soil organic carbon and thus favours carbon sequestration with positive impacts on climate change mitigation, and increases soil fertility, which contributes to improved yields and thus increase food security[94]. Agroecological practices also reduce pesticide use, increase biodiversity, and promote water conservation, with positive outcomes on ecosystem health and food security[95]. The energy transition towards renewable sources, implemented through spatial planning and citizen participation, enable co-usage of land, with positive impacts on energy security and ecosystem health. Finally, actions aiming at reducing water consumption, reduce energy demand and thus, greenhouse gas emissions. These adaptation measures reverse the feedback loop of the sectoral approaches that further deteriorate water and energy resources, food and ecosystem health and amplifies climate change, into a positive feedback loop among WEFE components (Fig. 3, left-hand side) that also mitigates climate change (Fig. 3, right-hand side).

The review provides clear evidence that there is a critical lack of complete and disaggregated data on the components of the WEFE nexus in the Mediterranean region. Even where data exist, they are often inconsistent or not comparable. Additionally, restrictions imposed by certain authorities on access to specific types of observations further hinder comprehensive assessments. Despite these limitations, the available data do allow for an assessment of nexus initiatives. However, a broader evaluation of their overall impact and the full realization of the WEFE nexus approach would require systematic and harmonized data collection to ensure consistency, accuracy, and accessibility[68,96–98]. Addressing these gaps is a prerequisite for fostering nexus solutions, and could be advanced by the adoption of common standards, the exchange of information across countries, and the promotion of international coordination and transnational projects. One concrete step in this direction is the EU requirement that all EU-funded projects deposit their data and materials in ZENODO, a general-purpose open research repository. Projects also involving non-EU Mediterranean countries would improve data comparability and availability, thereby enabling more robust and actionable nexus-based policymaking.

Conclusion

In the water-scarce Mediterranean basin, climate change negatively affects WEFE components both separately and through the cascading effects resulting from the interactions among them. Silo approaches contribute to

amplify the negative impacts while nexus-based technological, ecosystem-based and behavioural solutions enhance synergies within the interactions among WEFE components and climate change, while at the same time reducing greenhouse gas emissions and fostering carbon storage. A more quantitative approach is needed to assess to what extent nexus approaches can break the chain of cascading detrimental effects of climate change and how much the different strategies contribute to enhance those synergies. This would help identify the most efficient options, selecting those strategies that have higher positive impacts in the different WEFE components in different contexts. Model-based nexus approach assessments, or based on different climate, socio–economic and demographic change scenarios may help assessing the resilience level of adaptation measure options and avoid maladaptation and unanticipated effects when changing variables in the system. This should be considered when designing integrated policies[74,99–102]. To safeguard the Mediterranean's future, policymakers, researchers, and stakeholders must prioritise integrated, data-informed strategies that leverage the transformative potential of nature-based and equitable consumptive solutions.

The WEFE nexus finally offers a powerful integrative framework for addressing the interdependencies among water, energy, food systems, and ecosystems—resources that are fundamental to human development and ecological stability and reduces the risks of sectoral Sustainable Development Goal (SDG)[103,104]. In the context of the water scarce Mediterranean Basin, achieving SDG 6 (clean water and sanitation for all) is of particular urgency where water stress poses a critical barrier to progress across multiple SDGs, and particularly SDG 2 (zero hunger), SDG 7 (affordable and clean energy), SDG 13 (climate action), SDG 14 (life below water) and SDG 15 (life on land)[23].

The Mediterranean Basin's experience is highly relevant beyond the region itself. Other Mediterranean-type climate regions —including California, central Chile, the Cape Region of South Africa, and southwestern Australia—share distinctive features such as hot, dry summers, cool, wet winters, high biodiversity, and long histories of intensive human–environment interactions[105]. These regions face similar challenges of water scarcity, ecological stress, and land-use pressures[106]. Recent analyses also show that Mediterranean-type climate regions exhibit comparable climate dynamics, including variability in rainfall, drought frequency, and temperature extremes[107]. Such commonalities in climate, ecosystems, and human systems suggest that the nexus challenges highlighted here for the Mediterranean—particularly persistent water scarcity, rebound effects from technological fixes, and fragmented governance—are equally relevant in other Mediterranean-type climate regions. As such, the Mediterranean provides a valuable reference point for designing nexus-based strategies that can be adapted to enhance resilience in water-scarce regions worldwide.

Methodology

An open call for Mediterranean experts across the four domains of the WEFE nexus was initiated by the Mediterranean Experts on Climate and environmental Change (MedECC) network, inviting a diverse pool of candidates to apply. A selection committee composed of senior experts from various disciplines and countries within the region then evaluated and selected authors based on criteria ensuring geographic, sectoral, expertise, and gender balance. To refine the scope and objectives, a series of digital workshops were held to facilitate interdisciplinary discussions. Following this, a designated team—supervised by senior experts—was tasked with systematically identifying, reviewing, and synthesizing relevant literature within each domain. The review began with a clear definition of its objectives: to identify the key climatic changes and assess their impacts on the water-energy-food-ecosystems (WEFE) sectors, with particular attention to cascading effects. A systematic literature search was conducted using academic databases including Scopus, Web of Science, and Google Scholar, focusing on peer-reviewed articles. The search strategy combined keywords related to climate change, sector-specific impacts (water, energy, food, ecosystems), and interlinkages between sectors. For interlinkages, only studies addressing at least two nexus domains were included. Articles that were purely theoretical and lacked empirical evidence were excluded. Screening was conducted in two stages: first at the level of titles and abstracts to remove irrelevant studies, and then through full-text reviews to ensure relevance, rigor, and quality. For adaptation and mitigation solutions, Scopus and Web of Science were again used as source databases, with keywords including "WEFE nexus", "Mediterranean", "adaptation", and "mitigation." Given the relatively limited literature explicitly framed in terms of WEFE, we also considered studies dealing with integrated water resources management (IWRM) or other sectoral approaches when they addressed interconnections with additional nexus sectors. Selected papers were required to present an empirical assessment of implemented options in the Mediterranean context (see Supplementary note for more details on the review and categorization method). To assess the robustness of the findings, the number of papers evaluating a specific measure (amount of evidence) and the degree of consistency among them (level of agreement) were examined. The amount of evidence available is quantified by the number of articles addressing the specific topic investigated. The degree of agreement measures the consensus on the given topic. It is assessed from the fraction of articles that agree on the results (see Supplementary Table SM5). The terms for evidence are limited, medium, or robust. The terms for the degree of agreement are low, medium, or high. For findings with 'high agreement' and 'robust evidence', a level of confidence is given, as well as for findings with 'high agreement' or 'robust evidence'. The assessment of complexity and transformative potential was based on the published Mediterranean literature evaluating specific adaptation and mitigation measures. Solutions that showed trade-offs or mixed outcomes across components were classified as complex or controversial, while those consistently generating positive effects across the four nexus components were classified as transformative. The resulting categorization is illustrated in Fig. 2, which shows that while some solutions targeted all four nexus components, others were more narrowly focused on a subset of them.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

P. Drobinski, M.G. Rivera Ferre and M. Abdel Monem developed the assessment protocol and convened the author team; all authors contributed sectoral knowledge and text; P. Drobinski and M.G. Rivera Ferre wrote the paper.

Competing interests

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Additional information

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