



# Conceptualization of NEXUS elements in the marine environment (Marine NEXUS)

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## Abstract

The conflict activities observed in the marine environment, such as renewable energy production, aquaculture and tourism, highlight the need for more coherent management at the cross-sectoral level so that human activities in the ocean can be carried out in an efficient, safe and sustainable way. Along these lines, this paper focuses on identifying the interlinkages between the main natural resources in the marine environment, namely water, energy, marine land use, food and climate, by considering them to be nexus elements (Marine NEXUS). In addition, it tries to determine the interactions among them in order to identify the pressures on marine natural resources and their potential for use in the development of coastal communities. An analysis of the estimated interlinkages and complex pathways is performed, based on their impacts on every aspect of the marine environment in Greece. One of the main conclusions drawn from this analysis is that seawater has a very strong impact on food (i.e. the fisheries and aquaculture, in comparison with energy production in the sea). The choice of activities that may be implemented in the oceans (land use element) has a great impact on the food (e.g. fish quantities) and water (e.g. marine pollution) elements of the Marine NEXUS. The influences and the dependences of these five elements are quantified in order to show that the efficient management of natural resources requires a holistic approach that considers the cumulative impacts of the complex interactions among them.

**Keywords** Water-energy-food NEXUS · Climate change · Marine land uses · Coastal and offshore environment · Maritime spatial planning and policy · Natural resources

## Introduction

The marine environment is an important sector in the socio-economic development of Europe, as it supports many economic activities in coastal and offshore regions. In the last decade, there has been rapid technological progress in the development of coastal and marine activities carried out a short distance from the shoreline (Cariou et al. 2019). It is obvious that, due to the finite resources of terrestrial land,

there is a need to examine the maritime space in terms of supplying goods such as food and energy in a more sustainable way (Clement and McCullen 2002). In addition, the need to mitigate greenhouse gas emissions (GHGs) has led to the development of offshore infrastructure for the exploitation of renewable energy sources (Currie and Wovk 2009), food production and as tourist attractions. These conflicts observed in the marine environment highlight the need for more coherent management at the cross-sectoral level, so that human activities in the ocean can be carried out in an efficient, safe and sustainable way. In addition, the lack of maritime spatial planning in countries such as Greece slows down the sustainable development of marine areas and the equitable and efficient use of their marine resources (Tsilimigkas and Rempis 2017). Many research works related to the negative impacts of climate change on marine primary production (Brander 2010), human health and well-being (Carleton and Hsiang 2016; Toller et al. 2011) and coastal infrastructure (Malliouri et al. 2021) have been reported in the literature. In the recent work of Maltby et al. (2022),

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a marine climate change risk assessment was undertaken in a subtropical marine area to identify and prioritize climate risks and/or opportunities falling into the categories of “risks to biodiversity” and “risks to economy and society”, including the degradation of coral reefs, shifts in the distribution of wild-capture fishery resources, impacts on coastal communities, and threats to infrastructure and the aquaculture industry, highlighting the need for coordinated action and cooperation at multiple scales. Thus, the need for better governance of human activities in the ocean space and the necessity of a holistic, ecosystem-based and knowledge-based approach are now priorities. Winther et al. (2020) proposed a specific approach aiming to ensure the sustainability and resilience of marine ecosystems while integrating and balancing different ocean uses to optimize the overall ocean economy. Also, Papadopoulou et al. (2022) adopted a nexus approach for Greece, underlining the need to analyse complexities, motivate systemic thinking and develop integrated policies targeting the sustainable and efficient use of natural resources. As a result, the concept of the Marine NEXUS is introduced in this paper to try to determine the effects of the various elements of the marine environment—as previously defined—on each other under the influence of climate change. The aim is to identify the pressures on marine natural resources and their potential for the development of coastal communities.

Similarly to the work of Levistona and Walkerb (2018), which recognized interlinkages between ecosystems and human well-being, the analysis of Marine NEXUS interlinkages presented in this paper attempts to correlate the impacts of the variability of each NEXUS element on the others in the marine environment. In the context of climate change, the Marine NEXUS elements are related to the characteristics of seawater, the uses of the marine space, such as energy production, and its relationship with the marine environment and food production from the sea. The paper attempts to first identify and then quantify the interlinkages between these elements in the Greek maritime territory. The aim is to determine the interdependencies and obtain data on the maritime sectors to which special attention should be given in the context of the development of the Greek maritime spatial planning policy. More specifically, this paper will try to identify the hotspots that are difficult to manage and the maritime space areas that will potentially affect.

## The Marine NEXUS

The NEXUS approach has recently gained the role of a holistic approach that should be adopted in order to obtain resource efficiency at various scales and levels (i.e. scientific understanding and decision-making) (Susnik et al. 2018; Laspidou et al. 2020; Bakhshianlamouki et al. 2020).

Concerning policies, the NEXUS approach focuses on policy coherence analysis, a systematic way to identify trade-offs and synergies between policies across sectors. A first attempt to investigate water–energy–land–food–climate policies in Greece within a nexus framework was made by Papadopoulou et al. (2020). The adopted methodological approach placed emphasis on the exploration of possible options to better integrate policies across sectors for the sustainable development of all nexus elements.

The Marine Strategy Directive (MSD) sets the framework to facilitate the development and coordination of diverse and conflicting activities such as fisheries and aquaculture, shipping, offshore energy production, shipbuilding, and maritime and coastal tourism, with one of the aims being to maximize the sustainable development of marine areas, improving the quality of life and building the necessary knowledge for maritime policy. Among the outcomes of the MSD is a better understanding of human activity pressures and impacts on the sea, including their implications for marine biodiversity, habitats and ecosystems. Considering seas and oceans as the ground where various diverse human activities may take place, the concept of the Marine NEXUS is developed here to address their various impacts on marine natural resources in a more holistic approach.

Climate change, seawater, energy, food, and marine land uses are defined in this analysis as the five elements of the Marine NEXUS. Each element is connected to and interacts with the others through numerous interconnections. Laspidou et al. (2019) proposed a quantitative and qualitative methodology to assess these interlinkages among water, energy, food, land use and climate in the terrestrial environment. In this paper, the approach proposed by Laspidou et al. (2019) was adapted to the corresponding five elements of the NEXUS in the marine environment. A direct interconnection between two elements is defined as the influence that one element (e.g. climate) has on another (e.g. seawater), assuming that the rest (e.g. marine land uses, energy, food) remain unaffected. Symbolically, the direct interconnection of climate (C) and seawater (W) is represented as CW, and includes all possible combinations where a change in climate may affect seawater. It is important to note that each interlinkage is unique and has an opposite direction characterized by different link elements. The process of defining all Marine NEXUS interlinkages is achieved by reviewing and analysing the literature to ensure that all aspects are included (Papadopoulou and Vlachou 2021).

In addition to first-order interlinkages (direct interconnections), the five Marine NEXUS elements under study can also be affected through indirect second- to fourth-order interlinkages (indirect interconnections), depending on the number of elements that interact. More specifically, a second-order interconnection between climate (C) and seawater (W) can be formed through energy (E), i.e. through a chain

**Fig. 1** Detailed development of direct and indirect interlinkages between climate (C) and seawater (W)

$$\begin{aligned}
 C \rightarrow W &= CW + \\
 &\quad CLW + CEW + CFW + \\
 &\quad CLEW + CLFW + CELW + CEFW + CFLW + CFEW \\
 &\quad CLFEW + CLEFW + CFLEW + CFELW + CELFW + CEFLW
 \end{aligned}$$

	W	L	E	F	C
W	Grey	Red	Green	Red	Yellow
L	Red	Grey	Red	Red	Red
E	Green	Green	Grey	Red	Red
F	Red	Red	Green	Grey	Yellow
C	Red	Green	Green	Green	Grey

**Fig. 2** Schematic representation of Marine NEXUS interlinkages. Green represents a “weak”, red a “strong” and yellow a “negligible” interlinkage

effect in which a change in climate can affect the energy sector which can then influence seawater. This interlinkage is denoted CEW, while, similarly, the CEFW and CELFW interlinkages are third and fourth order, respectively. All intermediate connections (such as CE, EL, LF and FW in CELFW) are considered direct. In order to identify all indirect interconnections between two elements, e.g. climate (C) and seawater (W), all direct and indirect interlinkages starting from C and ending in W are progressively constructed here, resulting in all possible combinations (Fig. 1).

### Qualitative and quantitative analysis of Marine NEXUS interlinkages

In order to model the Marine NEXUS interlinkages, a classification system was developed to classify the direct correlations of Marine NEXUS elements and create an initial assessment of each interlinkage in the Greek marine territory. This initial assessment was based on the literature to maintain simplicity and to avoid making assumptions and introducing uncertainties. A three-point typology was used to evaluate the intensities of these interlinkages, with each first-order interlinkage classified as “strong”, “weak” or “negligible” (Laspidou et al. 2019). The physical interpretations of all Marine NEXUS direct interlinkages are listed in Papadopoulou and Vlachou (2021), and the associated classifications are shown schematically in Fig. 2, each with a corresponding rating of having a “strong”, “weak” or “negligible” influence. The influencing NEXUS element appears in the row and the affected one in the column.

In the context of quantitative modelling for the classification of these interlinkages, the heuristic algorithm

**Table 1** Detailed calculation of all CW interlinkages

		1st order	2nd order	3rd order	4th order
1st order	CW	<b>60.00</b>			
2nd order	CLW	19.94	<b>19.83</b>		
	CEW	19.94	<b>19.63</b>		
	CFW	19.94	<b>19.83</b>		
3rd order	CLEW	19.94	19.83	<b>18.60</b>	
	CLFW	19.94	19.83	<b>19.37</b>	
	CELW	19.94	19.63	<b>19.18</b>	
	CEFW	19.94	19.83	<b>19.37</b>	
	CFLW	19.94	19.83	<b>19.37</b>	
4th order	CFEW	19.94	19.63	<b>18.42</b>	
	CLFEW	19.94	19.83	18.60	<b>15.09</b>
	CLEFW	19.94	19.83	19.37	<b>18.03</b>
	CFLEW	19.94	19.83	19.37	<b>15.77</b>
	CFELW	19.94	19.63	18.42	<b>17.10</b>
	CELFW	19.94	19.63	19.18	<b>17.84</b>
	CEFLW	19.94	19.83	19.37	<b>18.03</b>
	Total score:				<b>335.48</b>

The bold values are the final value for each interlinkage as it is calculated by Eq. 1

proposed by Laspidou et al. (2019) was only applied to calculate the effects of higher order (indirect) interconnections. Direct interconnections were assigned a value of 60 if they were “strong”, a value of 30 if they were “weak” and a value of 0 if they were “negligible”. In this analysis, only strong and weak interconnections were mapped, while the negligible ones were completely eliminated. The initial nodes ( $n_0$ ) were assigned a value of 20 ( $c_0 = 20$ ). The calculation of the influence of each interlinkage was achieved starting from the initial node and going through all available pathways to the final node (Eq. 1):

$$c_{i+1} = c_i - \left( \frac{1}{(5-i)!} \times c_i^\beta \right), \tag{1}$$

where  $\beta$  is equal to 2/3 if the interlinkage is classified as “weak” and 1/3 if the interlinkage is classified as “strong”.  $i$  is the number of nodes in the path, and ranges from 0 to 4.

For the climate (C)–seawater (W) interlinkage, all second-, third- and fourth-order pathways (15 in total) were calculated. As shown in Table 1, the total value of the CW interlinkage is the sum of the final values at the nodes.

Table 1 shows the results of the algorithm's calculations, including the estimated total value of each interlinkage. The larger the order, the smaller the final value that is added to the final sum.

The algorithm is an approximation that takes into account both the order and the power of each interlinkage. A path with a strong first-order interconnection and a weak second-order interconnection presents a higher score than a path with a weak first-order interconnection and a strong second-order interconnection. Furthermore, the greater the distance from the node, the smaller its contribution. Consequently, a fourth-order path does not present a higher score than a third-order path, as the distance is greater and its influence on the original node is weakened.

More specifically, for the interlinkage CLW, the first-order interlinkage (CL) is considered the initial node and the associated value is equal to 19.94 (for  $i=0$ ). Moreover, as far as the second-order interlinkage LW is concerned, the corresponding value is equal to 19.94 based on Eq. 1 for  $i=1$ . The  $\beta$  parameter equals  $1/3$  as the interlinkage LW is defined as being strong (Fig. 2). All values

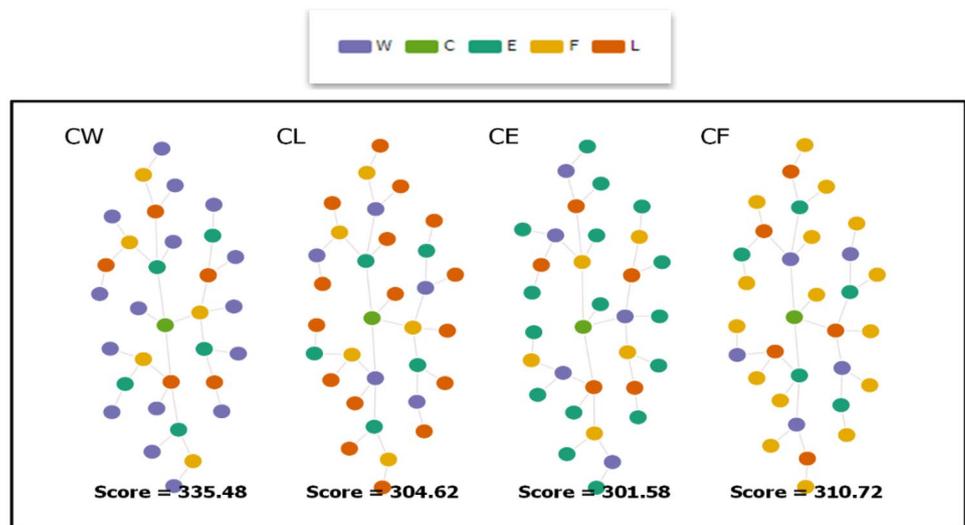
for the remaining interlinkages with  $i=2$  and  $i=3$  were calculated.

Figure 3 shows the interlinkages of climate with the other four elements of the Marine NEXUS, along with the corresponding values.

Table 2 summarizes the total influence and total dependence of each NEXUS element (rows) on the other NEXUS elements (columns).

Based on the information obtained in Table 2, it is the climate that influences the other elements of the Marine NEXUS the most (i.e. it has the highest row sum), whereas food is the most vulnerable of all the elements of the Marine NEXUS, as it is the most affected by the others (it has the highest column sums). This analysis shows that it is necessary to manage the effects of climate change by introducing measures to mitigate its impacts. Also, climate is a high priority, as investments in the maritime space, such as in the energy and food sectors, are highly dependent on the climate regime and determine the way and the means to manage these resources. On the other hand, fisheries and aquaculture (food element) and mainly seawater quality (water element) are strongly influenced by the other NEXUS elements, so

**Fig. 3** All climate element interlinkages along with the corresponding values



**Table 2** Total values of all NEXUS interlinkages in the marine environment

		Total Strength of Dependence					
		W	L	E	F	C	SUM
Total Strength of Influence	W		188,84	157,16	241,53	187,47	775,00
	L	282,40		224,83	283,27	152,94	943,44
	E	257,27	202,73		285,47	154,71	900,18
	F	244,43	189,40	157,83		187,28	778,95
	C	335,48	304,62	301,58	310,72		1252,39
	SUM	1119,58	885,60	841,40	1120,98	682,41	

measures related to those elements have direct impacts on the food dimension in the marine environment.

## Discussion

The total interlinkage value, including direct and indirect interlinkages to the other four elements, was quantified separately for each element of the Marine NEXUS. Based on the calculated values, the contribution of each interlinkage is also shown in Fig. 4. At first glance, it becomes clear that the interlinkages WF, LF, LW, EF and FW are more important than the others, meaning that specific elements of the Marine NEXUS interact strongly. One of the main conclusions drawn from this analysis is that seawater has a very strong influence on food (i.e. fisheries and aquaculture, in comparison with energy production in the sea). Also, the choice of activity implemented in the ocean (land-use element) has a great impact on the food (e.g. fish quantities) and water (e.g. marine pollution) elements of the Marine NEXUS.

In Fig. 5, the contributions of direct and indirect interconnections for all Marine NEXUS interlinkages are presented in a synthetic diagram, which shows that the strongest overall interlinkage is the one from food to climate (FC): even though the direct interconnection is classified as “negligible”, the higher-order route for FC is quite complex and has many nodes, resulting in a high indirect value. This result shows that indirect interconnections may play an important role in determining the total value of an interlinkage, and of course this finding should neither be ignored nor underestimated.

In this paper, a comparative analysis, using the method proposed by Laspidou et al. (2019), of the terrestrial and marine environments for the same five elements of the NEXUS (water, energy, food, land use and climate) is presented. In Fig. 6, the influence of the climate element in the Marine NEXUS is shown to be substantial higher than it is in the terrestrial NEXUS and compared to the other elements of the Marine NEXUS. A possible explanation could be the great importance of climate as a critical influencing factor in the development of the energy, food and water sectors in the marine environment.

For the dependence of each element, Fig. 7 shows that the dependence values of the water, energy, food and marine land-use elements of the Marine NEXUS are more

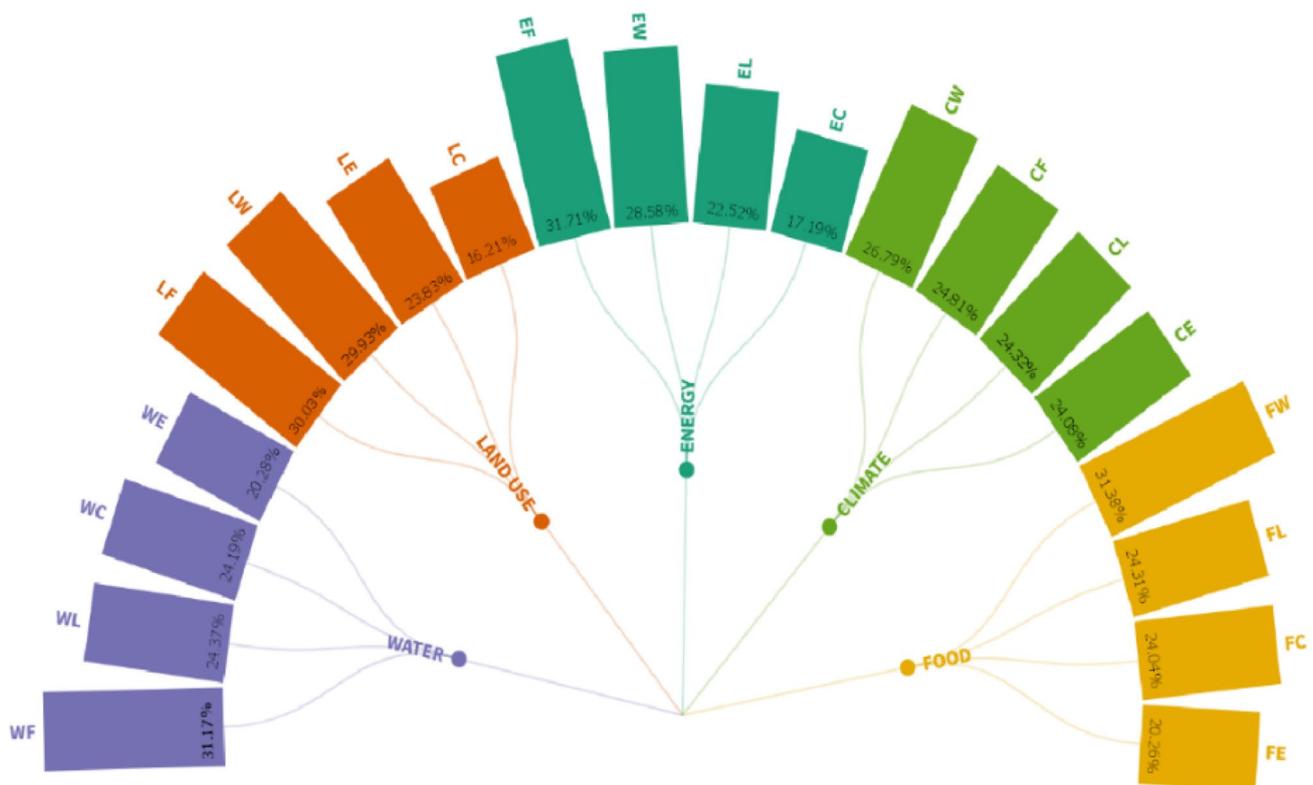
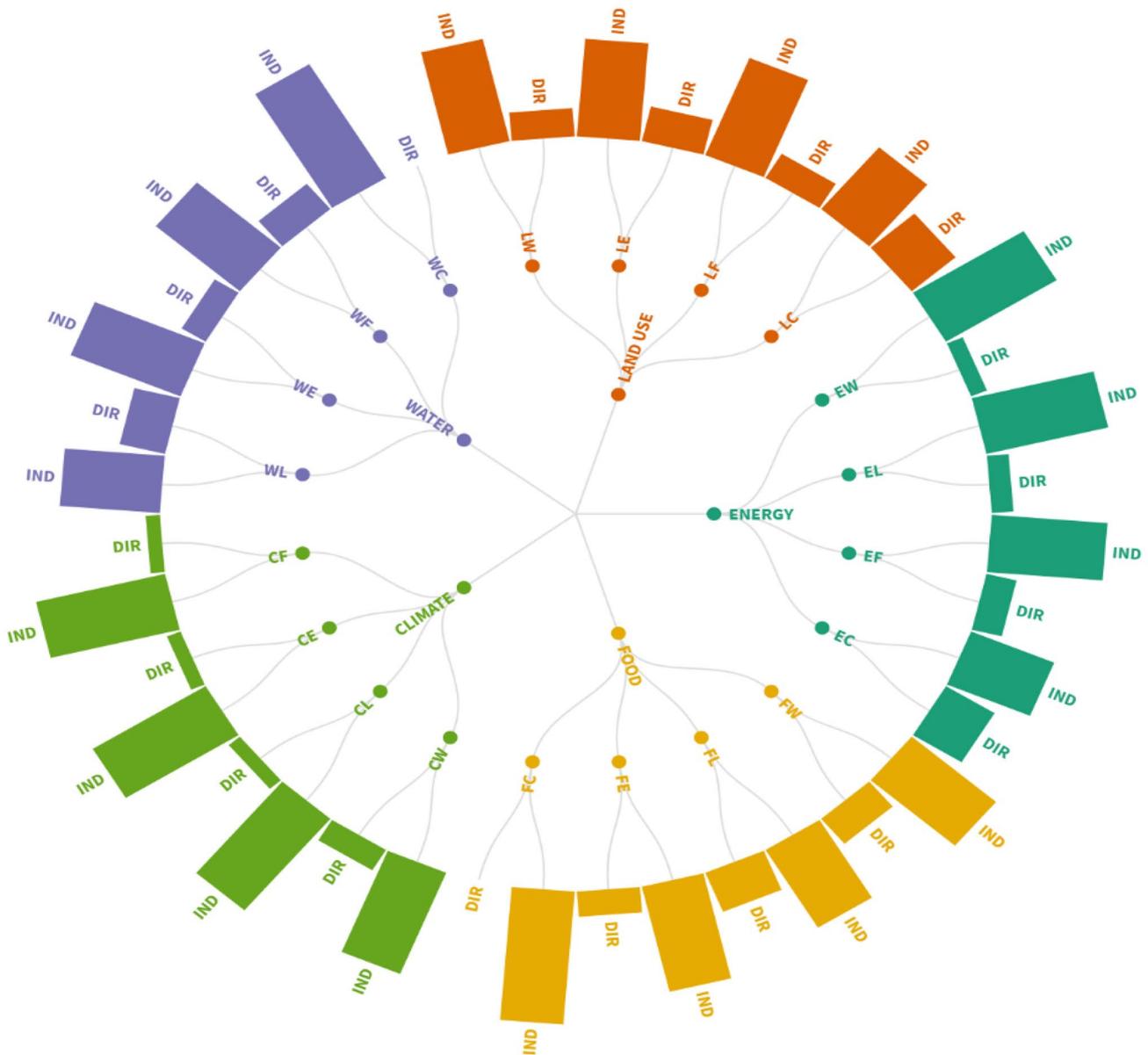


Fig. 4 The contribution of each element interlinkage in total



**Fig. 5** Contributions of direct and indirect interconnections for all Marine NEXUS interlinkages

substantial than that of the climate element, whereas in the terrestrial environment, the elements of the NEXUS have more or less the same dependence values.

## Conclusions

Based on the literature, all possible direct interlinkages between the five elements of the Marine NEXUS, namely seawater (W), marine land use (L), energy (E), food (F) and climate (C), were investigated and their interactions were developed, focusing on the causes of and influences

on the elements' parameters. An interlinkage can be direct or indirect, depending on whether a change to one element of the Marine NEXUS causes a change to another directly or through a third element or through several ones. A qualitative and quantitative approach proposed by Lapidou et al. (2019) was applied to quantify the influences and the dependences of these five elements in the marine environment. In this paper, a first attempt was made to quantify, in a systematic way, the complex physical nature of the interlinkages developed between water, energy, food, marine land use and climate. Moreover, a detailed calculation of all the interlinkages showed that the efficient management of natural resources requires a

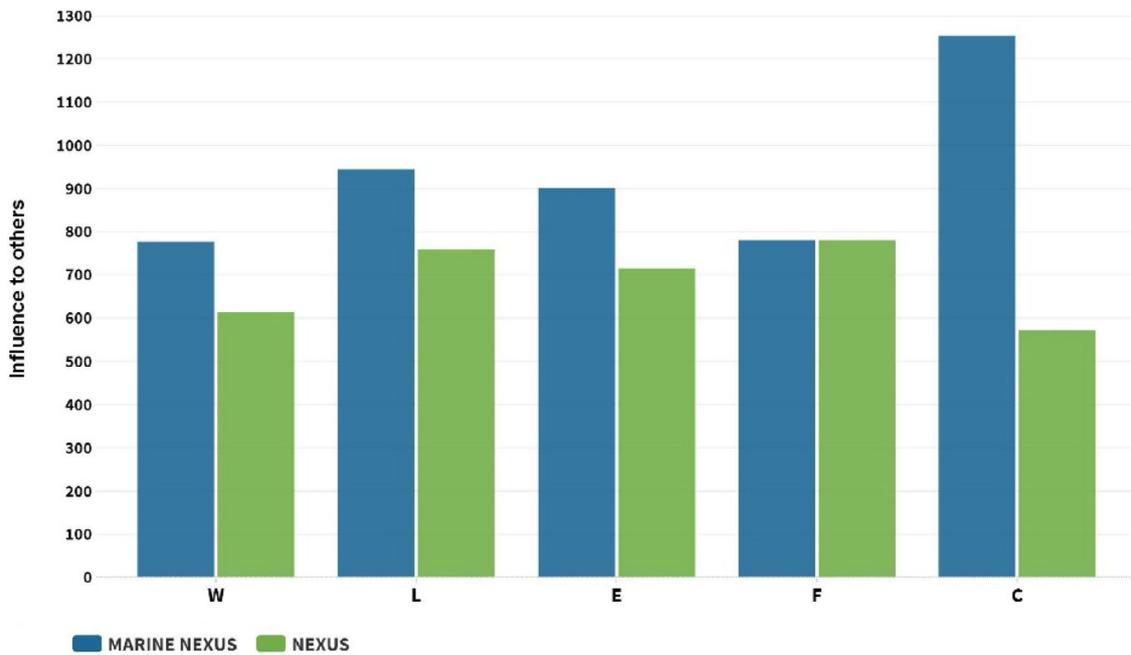


Fig. 6 Influence values for the five elements of the NEXUS in the terrestrial and marine environments

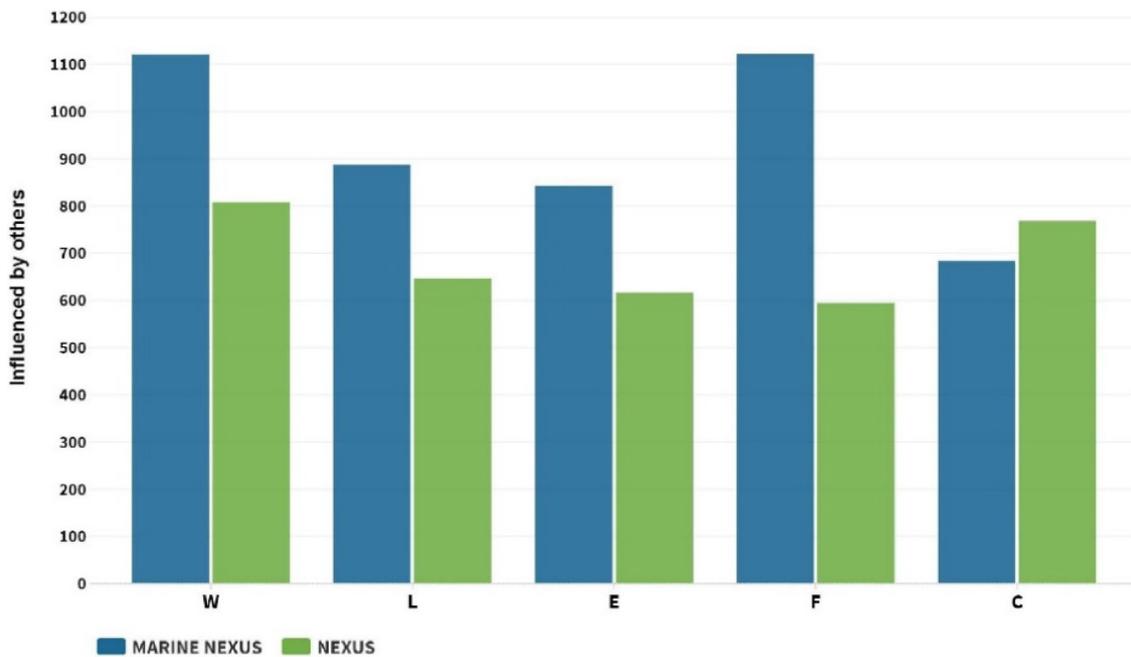


Fig. 7 Dependence values of the five elements of the NEXUS in the terrestrial and marine environments

holistic approach that considers the cumulative impacts of complex interactions among those resources in the context of the development of maritime spatial policy.

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## References

- Bakhshianlamouki E, Masia S, Karimi P, van der Zaag P, Susnik J (2020) A system dynamics model to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia Lake Basin, Iran. *Sci Total Environ* 708:134874. <https://doi.org/10.1016/j.scitotenv.2019.134874>
- Brander K (2010) Impacts of climate change on fisheries. *J Mar Syst* 79:389–402
- Carleton TA, Hsiang SM (2016) Social and economic impacts of climate. *Science* 353(6304):aad9837
- Cariou P, Parola F, Notteboom T (2019) Towards low carbon global supply chains: a multi-trade analysis of CO<sub>2</sub> emission reductions in container shipping. *Int J Prod Econ* 208:17–28
- Clement A, McCullen P (2002) Wave energy in Europe: current status and perspectives. *Renew Sustain Energy Rev* 6:405–431
- Currie DEJ, Wolk K (2009) Climate change and CO<sub>2</sub> in the oceans and global oceans governance. *Carbon Clim Law Rev* 3(4):387–404
- Laspidou C, Mellios N, Kofinas D (2019) Towards ranking the water–energy–food–land use–climate nexus interlinkages for building a nexus conceptual model with a heuristic algorithm. *Water* 11:306
- Laspidou C, Mellios N, Spyropoulou A, Kofinas D, Papadopoulou MP (2020) Systems thinking on the resource nexus: Modeling and visualisation tools to identify critical interlinkages for resilient and sustainable societies and institutions. *Sci Total Environ* 717:137264. <https://doi.org/10.1016/j.scitotenv.2020.137264>
- Leviston Z, Walker I (2018) Linkages between ecosystem services and human wellbeing: a nexus webs approach. *Ecol Ind* 93:658–668
- Malliouri DI, Memos CD, Soukissian TH, Tsoukala VK (2021) Assessing failure probability of coastal structures based on probabilistic representation of sea conditions at the structures' location. *Appl Math Model* 89:710–730
- Maltby KM, Howes EL, Lincoln S, Pinnegar JK, Buckley P, Ali TS, Al Balushi B, Al Ragum A, Al Shukail HSA, Balmes CO, Ben-Hamadou R, Claereboudt MRG, Mamiit RJE, Naser HA, Shokri MR, Le Quesne WJF (2022) Marine climate change risks to biodiversity and society in the ROPME Sea Area. *Clim Risk Manag* 35:100411. <https://doi.org/10.1016/j.crm.2022.100411>
- Papadopoulou MP, Vlachou A (2021) Investigating the water, energy, marine land uses, food, climate interlinkages in marine environment. In: e-Proceedings of 17th Int Conf on Environmental Science and Technology, Athens, Greece, 1–4 Sept 2021
- Papadopoulou CA, Papadopoulou MP, Laspidou C, Munaretto S, Brouwer F (2020) Towards a low-carbon economy: a nexus-oriented policy coherence analysis in Greece. *Sustainability*. <https://doi.org/10.3390/su12010373>
- Papadopoulou CA, Papadopoulou MP, Laspidou C (2022) Implementing water-energy-land-food-climate nexus approach to achieve the sustainable development goals in Greece: indicators and policy recommendations. *Sustainability* 14:4100. <https://doi.org/10.3390/su14074100>
- Susnik J, Chew C, Domingo X, Mereu S, Trabucco A, Evans B, Vamvakidou-Lyroudia LS, Savic DA, Laspidou C, Brouwer F (2018) Multi-stakeholder development of a serious game to explore the water-energy-food-land-climate nexus: the SIM4NEXUS approach. *Water* 10:139. <https://doi.org/10.3390/w10020139>
- Toller S, Wadeskog A, Finnveden G, Malmqvist T, Carlsson A (2011) Energy use and environmental impacts of the Swedish building and real estate management sector. *J Ind Ecol* 15:394–404. <https://doi.org/10.1111/j.1530-9290.2011.00340.x>
- Tsilimigkas G, Rempis N (2017) Maritime spatial planning and spatial planning: synergy issues and incompatibilities. Evidence from Crete island. *Greece Ocean Coastal Manag* 139:3341. <https://doi.org/10.1016/j.ocecoaman.2017.02.001>
- Winther J-G, Dai M, Rist Th, Håkon Hoel A, Li Y, Trice A, Morrissey K, Juinio-Meñez MA, Fernandes L, Unger S, Rubio Scarano F, Halpin P, Whitehouse S (2020) Integrated ocean management for a sustainable ocean economy. *Nat Ecol Evol* 4:1451–1458