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Systemic pathways to desirable futures: options for the marine ecosystem-based management of wicked problems

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Managing marine social-ecological systems requires governance strategies that account for uncertainty and conflicting stakeholder preferences. The Systemic Pathways to Desirable Futures (SPDF) framework is a tool for coordinating independent management actions in decentralized governance systems. It combines adaptive pathways metro maps, systems thinking, and ecosystem-based management with the Sustainable Development Goals (SDGs). The SPDF was applied in Europe, in Macaronesia (focusing on tourism), the Tuscan Archipelago (focusing on tourism and seagrass conservation), and the Arctic Northeast Atlantic Ocean (focusing on pelagic fisheries). Results indicate that every SPDF metro-map navigation involves trade-offs among associated SDGs and that choosing management pathways varies according to different worldviews. Furthermore, a coordinated option, which benefits most from the hierarchy between distinct pathways, reveals Macaronesia would promote SDGs 3, 8, 9, and 14, with trade-off of SDGs 12 and 16; Tuscany promotes SDGs 3, 6, 8 12, and 14 with no trade-offs; the Artic would promote SDGs 8, 14 and 16 with trade-off of SDG 13.

Governance of social-ecological systems (SES) involves managing the dynamic feedback between social and environmental interactions[1] and implies facing high levels of uncertainty due to the complex adaptive nature of these open systems[2]. The possibility of robust and long-lasting planning (i.e., that is not outdated by changes in the system, or opposed by different social groups over time), is therefore reduced especially in contested domains[3], such as climate change, transport, spatial planning and coastal governance. This reinforces the need for planning to be adaptive[4]. Addressing current local and global problems from the perspectives of system-thinking and wicked problems (i.e., seeing them as ill-defined, complex, and socially contested) increases the possibility of adaptive governance also being legitimate and robust. This is because these approaches start by framing these challenges by including at least two important characteristics of any SES: its dynamic complex behavior[5,6] and the socially contested nature of the problems definitions and solutions[7,8].

The use of scenarios and an ecosystem-based management (EBM) approach are complementary strategies that support SES governance. By bringing plausible descriptions of the future[9], and preferably with the help of models, scenarios can be complex, broad, and include qualitative narratives of the possible futures. In turn, EBM can enhance governance by incorporating system complexity and the socially diverse nature of the problems when it "recognizes coupled SESs with stakeholders involved in an integrated and adaptive management process where decisions reflect societal choice"[10]. As such, exploring the complex social-ecological relations and the possibilities for EBM by mapping the systems connections, synergies, and trade-offs embedded in distinct social perspectives is timely for the governance of SES and represents a knowledge gap this study will narrow.

There have been many attempts to conceptualize and manage highly uncertain problems such as marine SES governance or more broadly the challenges of the Anthropocene[11], Capitalocene, or Chthulucene[12]. Examples include structuring concepts such as VUCA, where the problems can be seen as Volatile, Uncertain, Complex, and Ambiguous[13], or the Decision-Making Under Deep Uncertainty (DMDU), where "components of a planning or management problem where decision-makers cannot agree

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upon the full set of risks to a system or their associated probabilities"[14]. We adopted in this study the idea of wicked problems[8] because it explicitly considers the conflicting social perspectives embedded in these problems and therefore provides crucial insights regarding the governance of ocean and coastal areas. Understanding conflicting social perspectives is crucial for the governance of some current (wicked) problems, for many reasons. The public policy field has long recognized that the central government's power is limited in terms of implementation, administration and control[15], and cannot democratically govern by just issuing edicts and assuming everyone would automatically obey. Plural actors influence the systems at large; conflicts over policy ends are ubiquitous as different groups give different priority to alternative goals[16].

Marine geographies represent the epitome of these SES governance challenges. Due to their transboundary nature, social-ecological complexities and uncertainties, and multi-stakeholder conflicts, they pose challenges that require new tools and approaches to support EBM and allow the integration of often independent initiatives into coordinated strategies. Indeed, coastal and marine areas are examples of both SES and wicked problems, since they are complex in terms of social-ecological interactions[17], their resilience varies according to the social group governing the system[18]; the framing of its problems can be contested, such as in fisheries[19] or marine protected areas[20], and finally these challenges have been exacerbated by climate change[21,22]. Therefore, what we present here is an interdisciplinary framework that embraces SES challenges, and focuses on the multiple framing societies will adopt to each problem. It builds on the causal connection observed in each system to develop pathways to act upon these problems and opens the governance ideas to plural participation.

The Systemic Pathways to Desirable Futures (SPDF) framework integrates a system thinking perspective[6], combined with EBM[23] and the wicked problems theory[7,8] as the theoretical backdrop, and builds on the dynamic adaptive policy pathway[24] as the visual and communication tool. The wicked problems approach is similar to the concept of messy problems[3,25,26] particularly in terms of governance complexity and social contestation. Both approaches can provide assistance where conventional tools revealed insufficient: "scientific uncertainty, indeterminacy, ambiguity and framing plurality means that conventional evaluation instruments like model predictions, cost-benefit-analyses or risk assessments are increasingly unsuitable for evaluating decisions"[27]. These tools, while still useful, require complementary approaches that can address growing tensions regarding the challenges humankind faces, the increasing complexity of social-ecological systems and the possibility of social contestation along with the governance process. Wicked problems bring to the center of the discussion the idea of epistemically plural policymaking, abandoning the one-solution-fits-all-problems approach to open space for more active participation of society, reflected by different worldviews. Accordingly, EBM prioritizes flexibility and adaptability, recognizing that both ecosystems and societies continuously change[10,28,29].

This paper aims to propose a structure to identify and coordinate distinct ways of addressing some of these challenges faced by coastal and marine SES, using the SPDF framework. It works by exposing a set of systemic pathways using metro-maps graphs, visual and structured representation of connections between elements in a system. These metro maps are made of pathways that represent sets of variables, systemically interconnected, that will influence the state of the problem or challenge to be governed. They can be used in a single use mode, for the individual management of a problem (in this case there is no social contestation of the problem and its solution), or to identify diverse management actions and efforts acting in the system and hence can be coordinated, promoting governance adaptability. Associated with each systemic pathway there are the most relevant United Nations Sustainable Development Goals (SDGs), and a specialist scientific accreditation revealing hot spots for management. We applied the SPDF framework in three distinct coastal and marine SESs across different European sea basins (i.e., the Arctic, the Atlantic and the Mediterranean). More precisely the testing took place in locations that serve as Demonstration Areas (DA) for the EU-funded Marine SABRES project, namely the Macaronesia, a set of three distinct archipelagos in the Atlantic Ocean, that in this project addresses governance of tourism, Marine Protected Areas (MPAs) and the potential establishment of a transboundary ecological corridor (i.e., protected areas where migratory species cross) connecting the Canary Islands (Spain) and the two Portuguese archipelagos of Madeira and the Azores; the Tuscan Archipelago, formed by a set of seven islands in the west coast of Italy, which focuses on the governance of tourism and its compatibility with the seagrass conservation; and the Arctic Northeast Atlantic Ocean, a extensive marine area formed by Iceland, Faroe Islands and east-Greenland seas, focusing on the pelagic fisheries management. See also Supplementary Materials A and B and Tables S1 and S2 for detailed descriptions of the problems.

Finally, a short glossary is provided to streamline the reading. We recommend the reader to visit the methods section for additional clarifications. For each pathway, three types of variables are included: Systemic pathway: is the group of variables connected in a causal chain, starting from a PESTLE variable of the causal loop diagram (Figures S2, S3 and S4), leading to the variable of interest and including any regular variable that might be present or not in between this causal chain; SPDF metro map: is a graph representation of a group of 1–6 systemic pathways and their interactions for a determined SES; Variables of interest: The main issue to address (e.g., tourism, fish landings), or usually considered "the problem" on which the governance system will act. This is the last variable in every pathway (the target); PESTLE Variables: Key starting points in the system (1–6). They are important variables identified by the group of experts as influential in the system; Regular Variables: Intermediate steps or stepping-stone connections between PESTLE variables to the variables of interest.

Results

Systemic pathways to desirable futures metro-maps

For each DA, the SPDF metro-maps start with the illustration of each causal chain and the connections each variable can promote in distinct pathways (Fig. 1a–c). Each pathway starts from a PESTLE (Political, Economic, Sociological, Technological, Legal and Environmental) variable (left) and ends with the variable of interest (right).

The SPDF metro-map from Macaronesia (Fig. 1A) shows a great convergence of political and legal pathways, marked by many synergies. Economic and social pathways are also connected with many synergies and large support from the social pathway to the economy. Both political/legal and economic/social pathways are disconnected from each other. The environmental pathway supports part of social/economic/technological pathways. The technological pathway is the most isolated. Migratory Fish and Habitat Quality are the main variables connecting all pathways to tourism.

The SPDF metro-map from the Tuscan Archipelago (Fig. 1B) has fewer synergies than the Macaronesian. The political pathway supports a great part of the social pathway. The environmental pathway supports the development of the technological pathway, leaving the legal pathway isolated and disconnected from the rest of the map, i.e., the only variable in the legal pathway is not appearing in any other pathway, and therefore, we cannot say it has been supported or is supporting anyone. This SPDF has a lock-in, as the social variable cannot have a causal chain that influences tourism activity. This means that if any actor in this system desires to influence the tourism activity by means of leveraging the well-being for locals (the main social variable) (see Supplementary Material B), it would automatically fail as there are no connections in the system that link these two variables. Blue Flags Program for beaches is the main variable connecting all pathways to Tourism Activity.

The SPDF metro-map from the Arctic Northeast Atlantic (Fig. 1C) shows the political pathway supporting the legal and social pathways. There is strong support from the legal to the social pathway. The environmental pathway is almost isolated, with a small support for the social pathway. The economic pathway is absent as the variable of interest is also the main economic variable (E) Landings. This metro-map shows two lock-ins as both economic and technological pathways do not reach the variable of

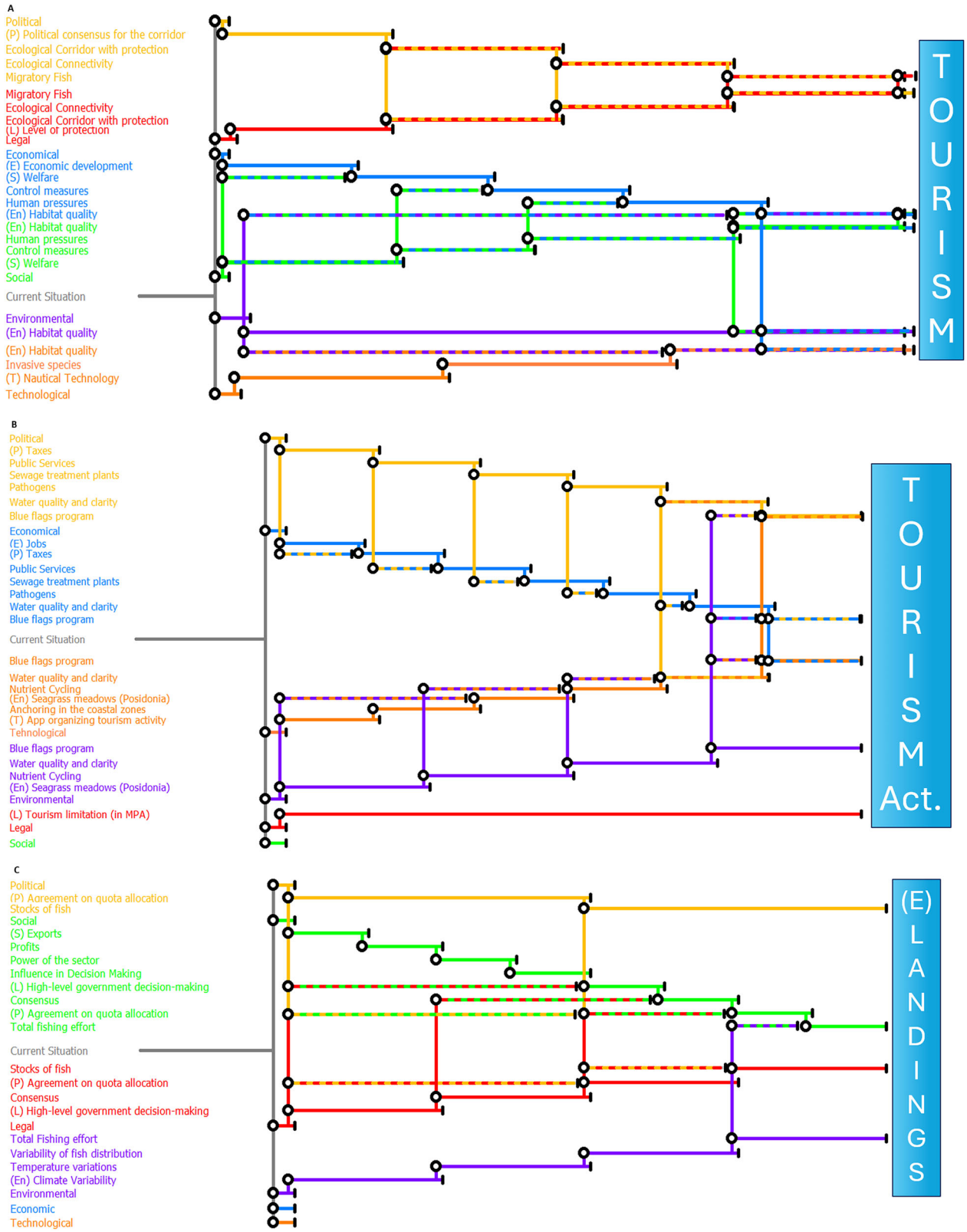

Fig. 1 | Systemic Pathways to Desirable Futures for each Demonstration Area (DA). A Macaronesia; (**B**) the Tuscan Archipelago; (**C**) the Arctic Northeast Atlantic Ocean. All DAs start at a current condition marked from PESTLE variables (left) and can navigate the pathway to influence the variable of interest (right side in blue). Tourism Act. is Tourism activity. Black circle: transfer station to a new route or new variable in the same pathway; Black vertical bar: limit of action of a variable in a causal chain; two lines of the same color connected horizontally: causal connection from two variables of the same pathway; one line with interpolated collors: a synergy between two pathways represented by each collor; one line with interpolated collors separated by a black vertical bar from an single color horizontal line: the interpolated pathway supports the single collor pathway; a short single collor line that does not connect with the variable of interest: a lock in.

interest. Stock of Fish and Total Fishing Effort are the variables connecting all pathways to (E) Landings.

Balancing - Representing hierarchy, synergies, and serendipities in the SPDF

This section is where the SPDF metro-maps (Fig. 2A–C) are fully developed to show: the hierarchy between pathways (represented by the background colour), the main SDG related to each variable (represented by the SDGs icons), and the scientific recommendation for management (represented by the black microscope icons).

In Macaronesia (Fig. 2A), the only enabler pathway in the SPDF metro-map (purple) is the environmental, in which the Habitat Quality variable can promote the economic, social, and technological pathways. There are independent pathways in the technological and the first steps of social and legal. The scientific recommendation was specifically to choose the Habitat Quality variable as a target for management (with three recommendation points). The other scientific recommendations were Level of Protection and Nautical Technology with two points each, with Economic Development having one recommendation point, and finally, one point in Human Pressures. The SDGs presented here are SDG 14 (life below water) as the main aspect related to these pathways. The economic/social pair brings a few additional Goals such as SDG 3 (good health and wellbeing), SDG 8 (decent work and economic growth) and SDG 9 (industry, innovation, and infrastructure). Finally, SDG 12 (responsible production and consumption) and SDG 16 (peace, justice, and strong institutions) are attached to independent pathways.

In Tuscany (Fig. 2B), there are more enabler variables (purple) from both political and environmental pathways (e.g., Taxes, Public Services, Sewage Treatment Plants, etc and Seagrass Meadows, Nutrient Cycling, Water Quality, etc., respectively) that support the economic and technological pathways (green). The legal pathway is the only independent pathway, and the social pathway is a lock-in. Synergies happen in the final variables close to the variable of interest, revealing a more intricate metro-map than in the case of Macaronesia. The scientific recommendations were stronger (three points) in Public Services, and in Seagrass Meadows, two points in Taxes, and in Water quality, and weaker in (one point) Blue Flag Program and in Tourism Limitation in MPA (Marine Protected Area). The SDGs represented are SDG 3 (good health and wellbeing), SDG 6 (clean water and sanitation), SDG 8 (decent work and economic growth), and SDG 14 (life below water) and all attached to an enabler pathway and the SDG 12 (responsible production and consumption) attached both to an independent and enabled pathway.

The Arctic (Fig. 2C) shows the legal and political pathways as enablers, with an additional single variable from the environmental pathway (Total Fishing Effort). The political pathway is the enabler of the legal, which in turn is an enabler for a great part of the social pathway (the longest in the causal chain). There are no synergies in this SPDF metro-map. There are two main independent pathways formed in the social (Exports, Profits, Power of the Sector, and Influence in Decision Making) and environmental pathways (Climate Variability, Temperature Variations, and Variability of Fish Distributions), and two lock-ins, one from the technological variable and the other from the economic. The scientific recommendations were stronger (three points) in Agreement on Quota Allocation, and in Stocks of Fish, two points in Total Fishing Effort, and weaker (one point) in Variability of Fish Distribution. The SDGs in this area presented less diversity and are more focused on governance, whereas SDG 16 (peace, justice, and strong institutions) dominates most of the SPDF metro-map. SDG 8 (decent work and economic growth) and 14 (life below water) were also present in enabled pathways. Finally, SDG 13 (climate action) appears related to an independent variable (Climate Variability).

Navigating the Systemic Pathways - a single use mode

Social choice in managing these SES problems is shown as options people might follow, starting from distinct worldviews. Many possible combinations of pathways are possible, with the eventual limitations of lock-ins that reduce the number of possibilities. In this exercise, a single use of the pathways is simulated according to worldviews, where some possible pathways (Fig. 3a–c) are represented, simulating the choices of the combinations of steps in variables of each pathway, a policy-maker would follow. Each of these pathways is formed by variables that are the causes of the behavior of the management target (i.e., Tourism, Tourism Activity and Landings). We invite the reader to follow these pathways as if they were managing each of these variables, and consider what happens with the SDGs and the scientific recommendations when following one pathway and not others (i.e., each choice might represent trade-offs in another pathway).

In the case of Macaronesia (Fig. 3A), hierarchy could start from different variables (political and legal), but as these pathways present synergies, they converge to the same point in Tourism; individualists could also have two different starting points (economy and technology), but both pathways restrict them toward reaching Tourism. Egalitarians have one main option, which leads directly to the variable of interest.

In Tuscany (Fig. 3B), the individualist could start with Taxes (political) or Jobs and Taxes (economical) and navigate their way towards the first opportunity of reaching the Blue Flags Program (in the environmental sector in this case). A hierarchical pathway could start with the isolated Tourism Limitation in MPA (legal) or with a more flexible Application to Control Tourism, making their way to establishing Water Quality standards and finally regulating the Blue Flags Program. The egalitarian would preferably start with the most important environmental variable in the model (the seagrass *Posidonia oceanica*) and follow its positive consequences through Nutrient Cycling, and Water Quality, finally participating in the Blue Flags Program due to the lack of a better conservationist option. A more reformist egalitarian could start with new jobs, taxes, and public services to finally reach the Sewage Treatment Plants, Pathogens, Water Quality and a later Blue Flags Program also due to lack of better options. Any pathway that would start from the social aspect would fail due to a lock-in.

In the Arctic case (Fig. 3C), a hierarchy approach has many pathways to follow, as the Agreement of Quota Allocation, Consensus, and High-level Government Decision-making are abundantly supported by other pathways, leading to the Control of Fishing Efforts, possibly maximizing economic yield and reducing environmental impacts. The individualist would probably start from Export and Profits, making their way to Control Fishing Efforts or Fish Stocks. The egalitarians would have difficulty in finding their way in this SPDF, probably going to an Agreement on Quota Allocation to finally reach a way to reduce the impact on the Fish Stocks. All possibilities of pathways in this SPDF are limited due to the lock-ins (technological and economic).

Navigating the Systemic Pathways - a coordinated SPDF grounded at the DAs

A summary of the results for coordinated navigation can be found in Table 1 (an integral description of the discussions regarding PESTLE element is in Supplementary Material A, a summary of "opportunities" is in Supplementary Material B).

For Macaronesia, a coordinated path would promote SDGs 3, 8, 9, and 14, to the detriment of SDGs 12 and 16, and follow 5 out of 10 scientific recommendations. The main enabler variable is Habitat Quality, and the opportunities raised in this realm were "possible ecolabel for tuna" (i.e., promoting fishing techniques that minimize bycatch and encouraging the use of biodegradable products to reduce the environmental impact of fisheries); therefore, the identified coordinated effort can start by promoting the ecolabel. Considering the other political, legal, economic, and social pathways present great synergies, the opportunities that were unearthed with the group model-building workshop (e.g., "offshore MPAs", "align with successful ecotourism models", "promote ocean literacy", and others) are adequate to form a positively reinforcing group of interventions. Finally, technological options such as the ones to reduce collisions with mammals represent a choice that is disconnected from the other pathways. SDG 12 (responsible production and consumption) and SDG 16 (peace, justice, and

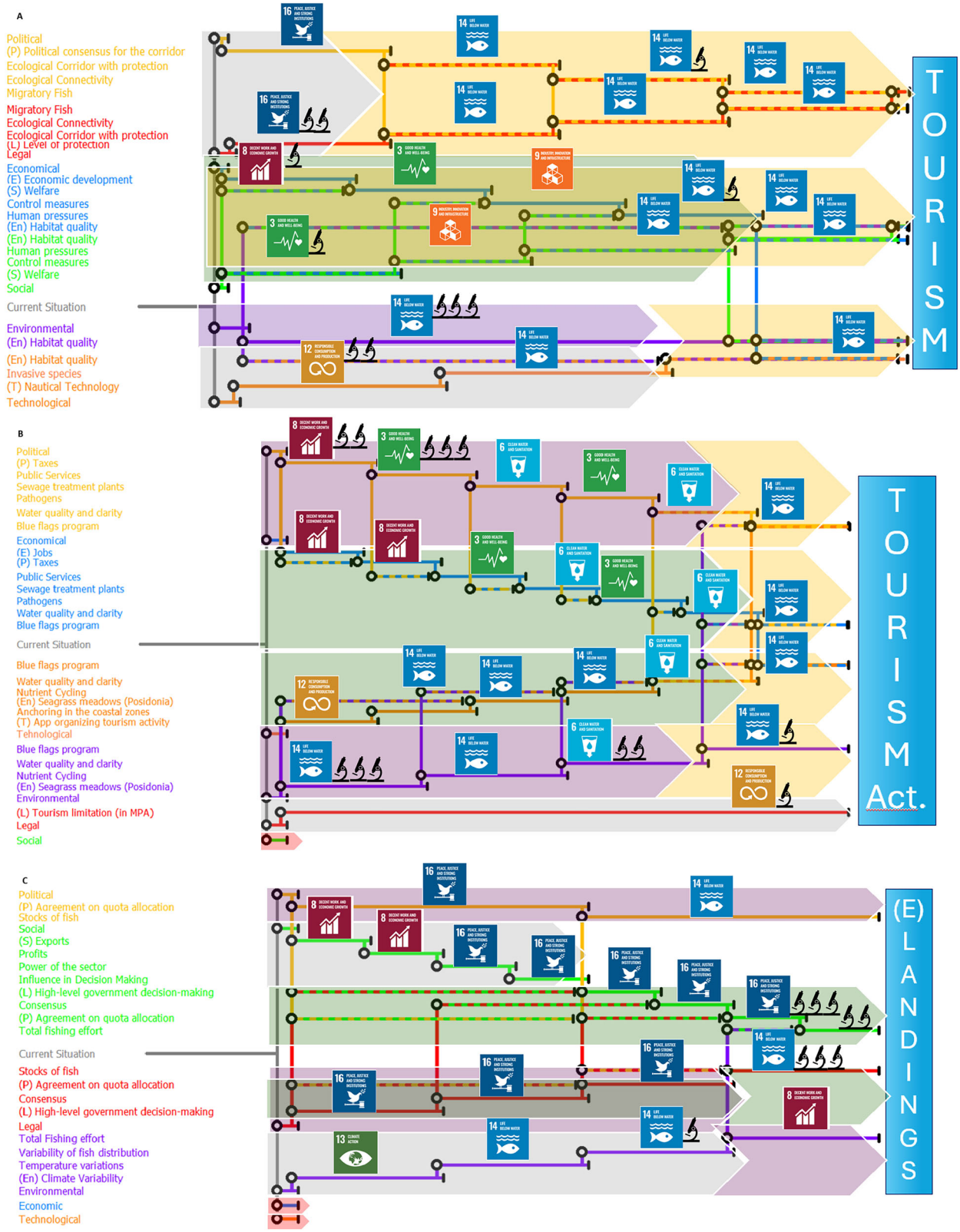

Fig. 2 | Systemic Pathways to Desirable Futures metro-maps. A Macaronesia; (**B**) the Tuscan Archipelago; (**C**) the Arctic Northeast Atlantic Ocean. All DAs start at a current condition marked from PESTLE variables (left) and can navigate the pathway to influence the variable of interest (right side in blue). Tourism Act. is Tourism activity. Black circle: transfer station to a new route or new variable in the same pathway; Black vertical bar: limit of action of a variable in a causal chain; two lines of the same color connected horizontally: causal connection from two variables of the same pathway; one line with interpolated collors: a synergy between two pathways represented by each collor; one line with interpolated collors separated by a black vertical bar from an single color horizontal line: the interpolated pathway supports the single collor pathway; a short single collor line that does not connect with the variable of interest: a lock in. A small icon of a Sustainable Development Goal: a SDG this pathway is promoting; an icon of a microscope: refers to a pathway that was recommended by the expert scientists consulted; background collor code: purple – enabler pathway; green- enabled pathway; yellow – synergistic pathway; grey – an independent pathway and red – a lock in.

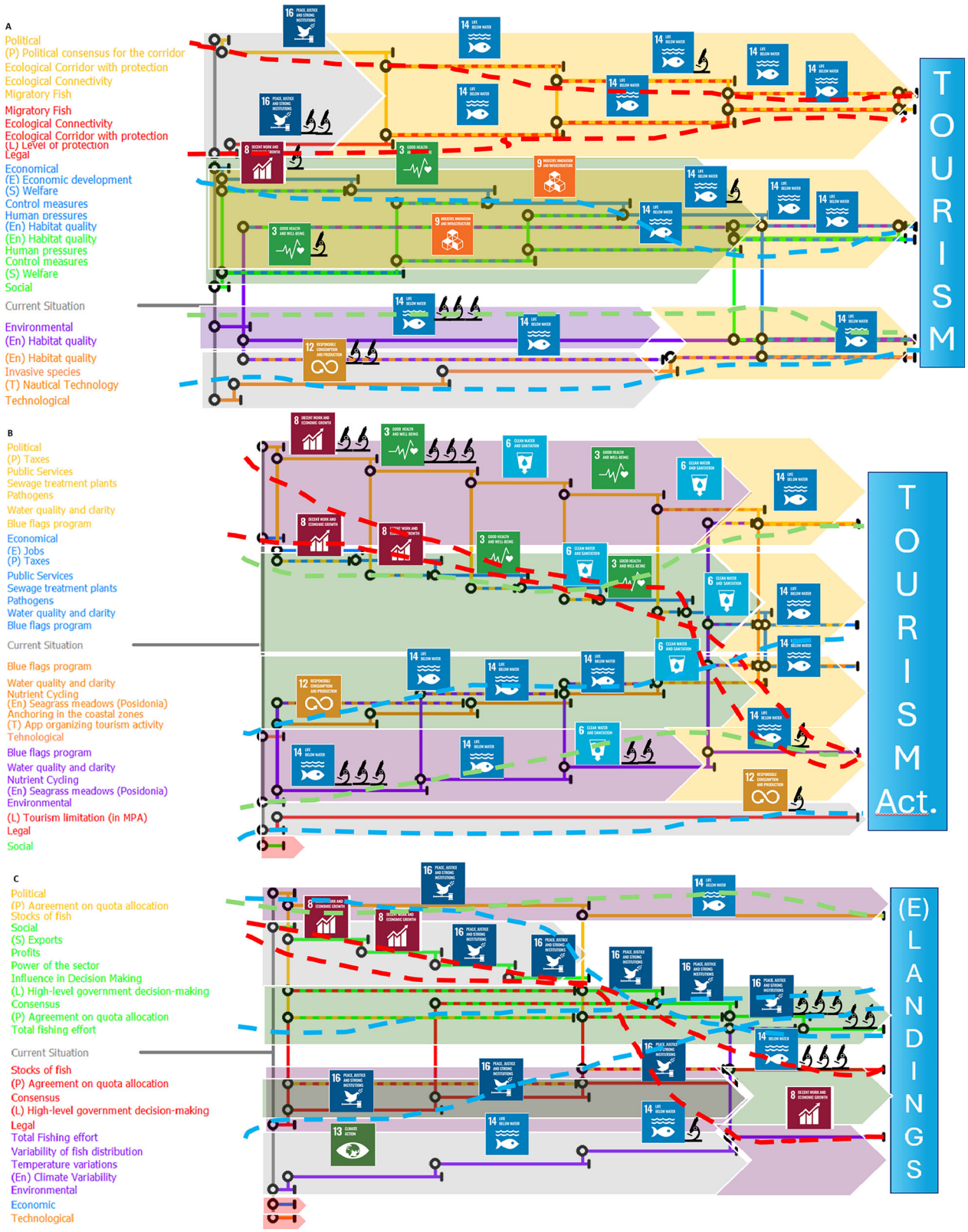

Fig. 3 | Navigating the Systemic Pathways to Desirable Futures for each Demonstration Area (DA). A Macaronesia; (**B**) the Tuscan Archipelago; (**C**) the Arctic Northeast Atlantic Ocean. Tourism Act. is Tourism activity. Black circle: transfer station to a new route or new variable in the same pathway; Black vertical bar: limit of action of a variable in a causal chain; two lines of the same color connected horizontally: causal connection from two variables of the same pathway; one line with interpolated collors: a synergy between two pathways represented by each collor; one line with interpolated collors separated by a black vertical bar from an single color horizontal line: the interpolated pathway supports the single collor pathway; a short single collor line that does not connect with the variable of interest: a lock in. A small icon of a Sustainable Development Goal: a SDG this pathway is promoting; an icon of a microscope: refers to a pathway that was recommended by the expert scientists consulted; background collor code: purple – enabler pathway; green- enabled pathway; yellow – synergistic pathway; grey – an independent pathway and red – a lock in. A large red-dashed line: an individualist pathway; large blue-dashed line: hierarchical pathway and large green-dashed line: an egalitarian pathway.

Table 1 | Summary of the coordinated Systemic Pathway to Desirable Future navigation in Macaronesia, Tuscan Archipelago and Arctic Northeast Atlantic Ocean. SDG: Sustainable Development Goals. Ind. is for independent

	Macaronesia	Tuscan Archipelago	Arctic Northeast Atlantic Ocean
Pathway Hierarchy	Environmental: Enabler Political: Synergy (L) Legal: Synergy (P) Economic: Synergy (S) Social: Synergy (E) Technological: Ind.	Political: Enabler, Environmental: Enabler, Economic: Enabled, Technological: Enabled, Legal: Ind., Social: Lock-in	Political: Enabler (L), Legal: Enabler (S), Social: Enabled/ind., Technological: Ind., Economic: Lock-in, Technological: Lock-in
SDGs promoted	14 (Life below water), 3 (good health and wellbeing), 8 (decent work and economic growth) and 9 (industry, innovation and infrastructure)	3 (good health and wellbeing), 6 (clean water and sanitation), 8 (decent work and economic growth), 14 (life below water), 12 (responsible production and consumption)	16 (peace, justice, and strong institutions), 8 (decent work and economic growth), 14 (life below water)
Balance of Science Recommendations	5 (+) out of 10: +3 habitat quality, +1 welfare, +1 human pressures, −2 level of protection, −2 nautical tech., −1 economic develop.	11 (+) out of 12: + 3 in public services, +3 in seagrass meadows, + 2 in taxes, + 2 in water quality, + 1 blue flag program, −1 Tourism limitation in MPA	8 (+) out of 9: + 3 in agreement on quota allocation, + 2 in total fishing effort, + 3 in stocks of fish, −1 variability of fish distribution
Lock-in	None	Social	Econ. Tech.
Trade-offs (SDGs)	12 (responsible production and consumption), 16 (peace, justice, and strong institutions)	None	13 (climate action)

strong institutions) are attached to independent pathways and therefore, are a trade-off that this coordinated pathway would not be promoted.

For the Tuscan archipelago, this coordinated path would promote all SDGs 3, 6, 8, 12, and 14), and 11 out of 12 scientific recommendations. Here, the political and environmental pathways are enablers and, therefore, more "appropriate taxes" (eco-tax or reducing subsidies) and "education about the relevance of seagrass" are present as respective opportunities. The economic and technological pathways are facilitated by these previous actions and present their opportunities, also connected with political/environmental pathways, such as an "app informing tourists of the ecological significance of the area and seagrass (T)", and a "high-tech aquaculture plant (E)". Finally, "legal reinforcement" of the "monitoring with cameras" or others are options from the legal pathway, but independent from other pathways. No trade-off was found in this SPDF metro-map in terms of SDGs.

Finally, for the Arctic Northeast Atlantic Ocean, the coordinated pathway would promote SDG 8, 14, and 16, to the detriment of SDG 13, and follow 8 out of 9 scientific recommendations. Here, the political pathway is the main enabler. Therefore, opportunities such as "certifications", "a dynamic quota depending on fish distribution", or "sanctions" are the better options. For the legal pathway, an opportunity would be to "connect the quotas to the fish stocks", promoting more adequate sharing and landings. From the Social pathway, "education about sustainability" and "consumer preferences" (connecting with labeling) are opportunities that can be explored. From the environmental pathway, which is independent of the others, "increasing efficiency from the fuels" and "improving the logistics of fisheries" are the latter opportunities. A trade-off between the coordinated pathway and SDGs 13 was identified as this SDG in an independent pathway.

Discussion

When the ideas regarding wicked problems emerged[8,30], they brought significant grounds for doubting the efficacy of purely technical approaches to public policy and planning[31]. The idea that solutions are not permanent, and cannot be elegant (i.e., not right or wrong, but good or bad for certain parts of society for a certain period) are still innovative despite being already applied to some marine science, for instance in fisheries[19], protected areas[20], EBM[25], and resilience[18]. As wicked problems ideas are also strongly aligned with Cultural Theory[32,33] that embraces the social differences in perception and preferences, both represent significant improvement toward the governance of contested problems[3,34]. Furthermore, broadening the problem definition/solution to multiple views also contributes to align the approach presented in this paper, with the principles of post-normal science, an interdisciplinary vanguard approach that aims to contribute for legitimacy and participation in the current global problems[27,35,36].

This plurality of perspectives and governance options are mapped and coordinated with the SPDF metro-maps and thus can promote the resilience of the SES in two forms: first because by mapping plural pathways with different views, frames, and solutions, it often keeps the "options for the future" available[37], echoing both the foundational ideas of the adaptive pathways literature "maximizing flexibility by keeping options open and avoiding 'lock-ins'"[38], but also the EBM foundational literature e.g., see refs. 39,40. In our study, results (Table 1, Figs. 1, 2, and 3) show that the options in the Arctic Northeast Atlantic are reduced by two lock-ins and the Tuscan Archipelago by one, while Macaronesia maintains all pathways available. Second, by revealing synergies and enabled pathways, it often identifies redundancies in the causal chain leading to the variable of interest (i.e., Tourism, Tourism Activity, and Landings), a characteristic of a SES directly related to its resilience[2]. In our study, results (Figs. 1, 2, and 3) show the Arctic Northeast Atlantic with no redundancies (i.e., synergies), when compared with the Tuscan Archipelago, which has some redundancies and Macaronesia which has the most redundancies of the three DAs.

The hypothetical pathways drawn using the worldview preferences (Fig. 3a–c) are meant to be provocative to the reader in terms of showing that all preferences will have their pros and cons. They represent a single use mode of the SPDF metro-maps and do not intend to be exhaustive options that policy-makers could choose, but to streamline the main ideas of independent social choice, and its consequences. The single use navigation implies understanding that social choices do not happen in a vacuum. On the contrary, recognizing that both the problems and solutions belong to a determined social bias, here represented by worldviews[34,41–43]. These restrictions (from worldviews and trade-offs) constrain the problem to the real case, aligned with the ideas of situated wickedness[44].

In coordinated navigation (Table 1), Macaronesia would prioritize the environmental pathway as it is the enabler of the others, and then followed by political, legal, economic, and social as they are connected through

synergies. This navigation would follow most of what the "scientific recommendations" proposed, promoting trust in experts[45] and maximizing the side effects of SDGs[46]. Nonetheless, the DAs are in countries where progress on SDG12 has been poorer ref. 46 and in conflict with other SDGs ref. 70. Therefore, as several of the pathways identified do not involve SDG12 it might continue to be limited in this region.

For the Tuscan archipelago, the connections between seagrass and tourism that were elucidated with the CLDs[47] are clear, reinforcing the relevance of the political realm for the conservation of the seagrass meadows and their related ecosystem services[48,49]. In addition, by revealing in the model and pathway the connections of the seagrass to the broader system it is part of, this study corroborates previous understanding of seagrass as an SES[50] and provokes decision-makers to understand its governance more broadly.

Finally, for the Arctic Northeast Atlantic, the idea of coordinating independent actions toward a sustainable future is critical[51] and in the SPDF metro-maps, the political pathway is the main enabler. This is coherent with the current efforts in coordinating international fisheries agreements, but the political complexity of interactions between the national actors, particularly across European Union membership, renders this task challenging and can lead to fragmented agreements[52]. Other opportunities, such as "certifications", "a dynamic quota depending on fish distribution", or "sanctions" are reasonable options. The opportunities from the legal pathway, such as "connect the quotas to the fish stocks", could be challenging as the uncertainties regarding fish distributions are large and difficult to manage[53].

The governance implications of the SPDF framework can be manifold. The SPDF framework and metro-map focus on governance as a decentralized multi-actor process, usually studied under theories such as multi-level governance, collective action, network governance or any form of polycentricity[54], where decisions and management are made from a diverse set of (formal and informal) institutions and actors. In the field of adaptation pathways, this is a novelty as former ideas of adaptation pathways[55] consider a central decision maker.

The SPDF metro-maps allow distinct strategies to be coordinated horizontally (across geographic jurisdictions or policy areas) by different groups and sectors[56], to act on the problems from a systems perspective. We understand strategy "as a multi-component set of policy and program interventions, including system enablers, employed toward the achievement of an overarching outcome"[57] and claim the SPDF metro-maps contribute with a strategy as it allows for the articulation of interdependent, but operationally autonomous, actors from private and government sectors. This articulation has been appointed as a possible way to address wicked problems[56]. This trait further differentiates the SPDF from the previous uses of the metro maps, e.g., the DAAP[55,58], as it does not assume governance emerging exclusively from a powerful centralized agent, but rather being the result of plural, polycentric, and often contesting efforts. Finally, in Europe, the increasing role of decentralized implementation, for instance of global decarbonization goals, has also been highlighted by some authors e.g., see refs. 59,60. In addition, the present approach aligns with the context of new public governance (NPG) due to its pluralist governance ideas[61] toward which, we have shown, the SPDF can help integrate initiatives that "require collaboration and coordination between government and non-government actors"[57]. Furthermore, the hierarchy of pathways is directly aligned with the necessity of "determining system enablers", one of the five main attributes of a successful strategy for governance, under the NPG umbrella[57].

Another topic that can be of interest is the difference in scale between the case studies. While the Macaronesia DA (formed by two archipelagos from Portugal and one from Spain) and the Arctic DA (formed by the waters of Iceland, the Faroe Islands, and the east Greenland) could be taken as similar scale, the Tuscany DA (formed by seven Italian islands in the Mediterranean Sea) is significantly smaller. The SPDF framework does not acknowledge scale directly, but as the framework has two forms of navigation (single-use and coordinated) we expect that the single-use mode would make more sense in small-scale problems such as those represented by the Tuscan archipelago, in which the tourism/seagrass problem[62] is smaller when compared with the other two. In both Arctic DA and Macaronesia DA cases, negotiations involve different countries, and therefore the chance of having distinct cultures and values related to nature is larger, in which we could expect the coordinated navigation would be more appropriate as the necessity of accommodating plural interventions in the system, often conflicting for fisheries e.g., see refs. 63,64, and for conservation of species in internacional waters e.g., see ref. 65, would appear more adequate.

The discussion of what EBM is and how to do it is long and out of the scope of the present paper. We assume EBM is a common goal in coastal and marine governance and therefore, compared the ideas behind the SPDF with the main principles of EBM Long et al.[10]. We present this alignment with bullets from these principles: Consider ecosystem connection: SPDF metro-maps are directly obtained from causal loop diagrams[6]; Adaptive management: the main idea of SPDF by being based on the dynamic adaptive pathways[55] is to promote options and coordination where not only conditions but social choice change, therefore, being adaptive; Appropriate spatial and temporal scale: the SPDF is based on CLDs[47], and the sessions to build these CLDs discussed specifically the time frame and the spatial definition they are referring to (Supplementary Material B and C); Use of scientific knowledge: scientific knowledge was obtained by expert elicitation and used to build the CLDs, to establish connections between variables, and the pathways also include the recommendations for use of the SPDF metro-maps; Stakeholder involvement: one level of stakeholders was used to build the CLDs (scientists from each DA), this can be enhanced by including other stakeholder groups in the single use choice of their pathways or to rebuild the CLDs; Integrated management: as with the ideas in the social-ecological systems field[66], the SPDF integrates ecological and social variables by design and point to many frontiers in interdisciplinary knowledge (e.g., post-normal science and wicked problems); Sustainability: when taken as a goal, it can be promoted by the SPDF framework, according to different social choices and scenarios; Account for the dynamic nature of ecosystems: is a central idea as the SPDF metro-maps are based in CLDs, i.e., system dynamic models[67]; Ecological integrity and biodiversity: if these are taken as goals for management, they are embedded in the framework, otherwise not; Recognized coupled social-ecological systems: is central and includes the social-ecological systems, systems thinking and wicked problems perspective[3]; Decisions reflect social choice: for the SPDF this is central as the metro-maps reveal optional pathways and tradeoffs; Distinct boundaries: this topic is also discussed during the creation of each CLD[47]; Interdisciplinarity: as the central point in the SPDF are the CLDs, and they are intrinsically interdisciplinary[6]; Appropriate monitoring: as the SPDF is not prescriptive on monitoring, this is not foreseen in the framework; Acknowledge uncertainty: is central to the wicked problems, systems science and thus to the SPDF framework.

The limits and caveats of the present study start with the idea of converging in one framework ideas from distinct scientific traditions, such as the adaptation pathways roadmaps, systems thinking, toward the challenge of addressing wicked problems. We acknowledge that all Figures are complex, and rich in colors that might be difficult to understand for a color-blind person. In addition, the dependence on group "beliefs" of causal relations is a rationality limitation that has a long history in systems science[6,68]. Another limitation is in applying its guidance to ground problems, the level of development of our project and the limitations in reaching all policy-makers render the present study more theoretical. Finally, the CLDs in which this study is based reflect a vision of the system that was created by a limited set of experts from natural and social sciences. As these experts are mostly representatives of the natural sciences, this vision is limited to their expertise. We do acknowledge this as a limitation that can be overcome, for instance, by creating distinct CLDs representing each worldview from cultural theory, an approach similar to the soft systems methodology[69].

Lastly, coordinating plural efforts in a democratic society is challenging and climate change restrains the possible future towards a necessary greener

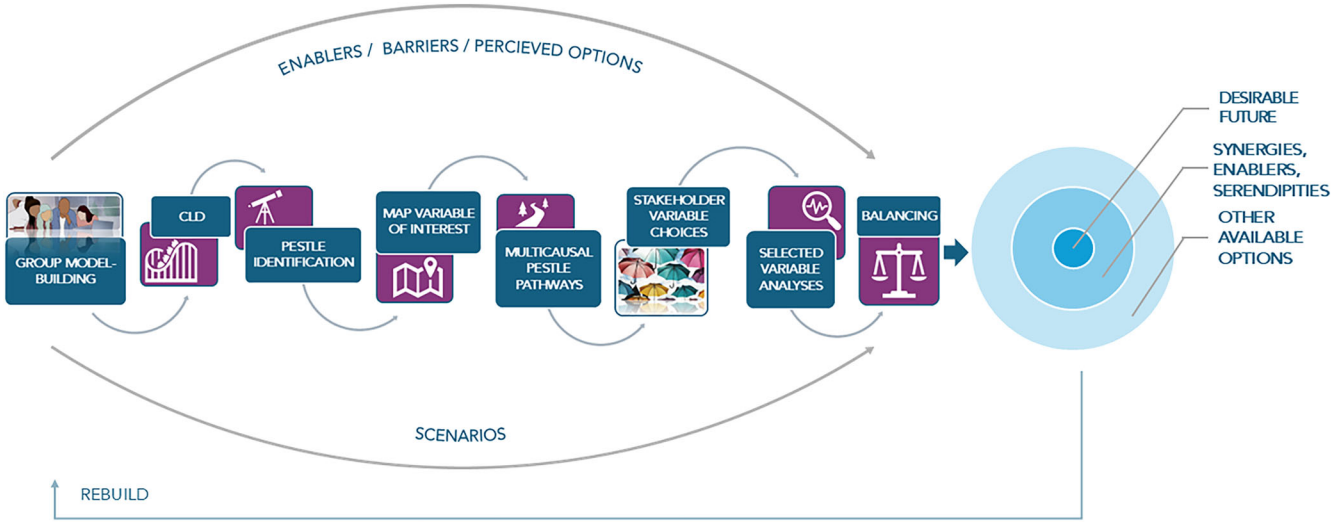

Fig. 4 | Starting from a group model-building exercise. A causal loop diagram (CLD) is developed, where the main Political, Economic, Social, Technological, Legal, and Environmental variables (PESTLE) and the variable of interest are identified. Causal chains from each PESTLE variable to the variable of interest are mapped. Consulting with specialists provides scientific accreditation (stakeholder variable choice) to each variable, that converges to the "point of balance" of options, synergies, and barriers. After balancing, i.e., consideration of opportunities, serendipities, trade-offs and synergies, the final product is a SPDF metro-map, that can be used in a single use mode to influence the variable of interest or to coordinate plural actions in decentralized governance systems. It is recommended to restart the cycle if actors' worldviews are not represented, or the system attributes change significantly.

(i.e., SSP1 or other similar scenarios) route for humankind's development. Understanding this challenge under wicked problems and systems thinking umbrellas can be promising as they do not avoid complexity; on the contrary, they center the view on the social and ecological interactions and uncertainties. What we suggest for future users of the present framework is to follow the guidelines of this study to create their own SPDF, specifically for the governance of problems that have been contested by different social groups. These can be, for instance, where recent "polarization" of society is present, such as in education, climate change adaptation, poverty, and others. What we expect from the use of SPDF is a clear view of where conflicting actors are leveraging the system, and therefore, a comprehensive strategy can be made to integrate these conflicting actions towards a coordinated output.

In the present study, we show that the SPDF can provide coordination amongst individual worldviews and actions, providing a theory of system hierarchy where some pathways can be supported and enabled by others, converging to a rationale to integrate governance towards a desired scenario of ecosystem-based management. The SPDF was tested in three European marine social-ecological systems, namely Macaronesia, Tuscan Archipelago, and the Northeast Arctic Atlantic Ocean, and revealed different coordinated pathways to the governance of their challenges. The opportunities and systemic enabled pathways are also provided with scientific recommendations and sustainable development goals as additional traits for a robust decision-making process. The SPDF proved to be a promising framework for integrated decision-making under plural worldviews and governance perspectives.

Methods

The SPDF framework embraces a process of systems investigation that will produce a metro-map of each SES, showing alternatives for single use navigation or coordination of diverse management options (Fig. 4). The connections with systems thinking, wicked problems and dynamic adaptive policy pathways are detailed in Supplementary Material D.

The SPDF was built on the results of a series of workshops dedicated to creating a systemic understanding of each DA, represented initially by Causal Loop Diagrams (CLDs) (Supplementary Material B), which map the system influencing the problem concerning each area (henceforth named the variable of interest). These workshops were conducted over two days each, between May and June 2024. Participants were comprised of experts, facilitators and observers, specifically 12 experts from Macaronesia, 4 from the Tuscan archipelago, and 10 from the Arctic. Experts, in the present context, are all those natural and social researchers that have a contract with the Marine SABRES project, which by the terms of this contract consent with the participation in the study, independent of their background, and are involved with the science or policy-making process in their respective DAs. The facilitator was the first author of this paper, as the leading person of the workshops, and observers were the coordinators of the project and another author of the present paper, who were supervising the workshop sessions. The workshops are described in depth in Oliveira et al.[47]. The SPDF framework also uses a summary of the qualitative descriptions of problems and solutions from each DA (Supplementary Material C), to create each metro-map.

The eight steps necessary for creating the SPDF metro-maps and navigating them

Group Model-Building:. Where participants constructed a CLD using VENSIM PLE (version 10.1) to map their system and the variable of interest (i.e., the problems at hand). The map represented a shared understanding of the system where management challenges occur, highlighting enablers, barriers, and opportunities for management options. These initial insights formed the basis for the next steps of SPDF development. The shared socio-economic pathway SSP1 ("Sustainability"; O'Neill et al., 2017) was adopted as a representation of the desired future in each area, reflecting the transformative changes requirement revealed beforehand in the project (Bremner et al., 2024).

Validation: The CLDs were thoroughly validated with a multi-dimensional protocol composed of 26 criteria organized in four dimensions (see Oliveira et al., 2025, for details). Such a protocol assessed each part of the modeling process and provided recommendations for improvement (as this step is optional, it is not represented in Fig. 4).

PESTLE variables identification: where critical system variables were identified by the group and categorized using Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) elements (Pinnegar et al., 2021). These variables will be the starting point of each systemic pathway (see below).

Variables of interest identification: The main issue to address (e.g., tourism, fish landings, etc.) in each area, identified in the CLDs and each SPDF metro-map.

Table 2 | Systemic relevance of pathways (hierarchy)

Color	Type of Pathway	Description
Purple	Enabler	By following this pathway, another pathway is benefited.
Green	Enabled	This pathway benefited from a previous pathway.
Yellow	Synergistic	When two pathways present the same variables at approximately the same step, reinforcing each other.
Grey	Independent	Cannot enable or be enabled by other pathways.
Red	Lock-in	There is no pathway connecting the PESTLE variable to the variable of interest.

Causal chains mapping: after the workshops, a set of causal chains was investigated to reveal the stepping-stone - i.e., any variable that is between the origin and destiny in the CLD. The same as the regular variables that "fills" the space between a PESTLE variable and the variable of interest - link between each PESTLE variable to the variable of interest (henceforward, a systemic pathway). The causal chains are central to the SPDF as they represent presumed causal relations between PESTLE variables (initial variable of each pathway) and the variable of interest (final variable of each pathway), and therefore, are mainly responsible for determining the behavior of the variable of interest. Each systemic pathway (i.e., the group of one PESTLE variable, the variable of interest, and any variables in between) was mapped based on the shortest causal connections between these boundary variables. In summary, a causal chain is a systemic pathway with an origin in a PESTLE variable and ends in a variable of interest. To avoid repetition, a systemic pathway henceforward will be named pathway. The group of several pathways and their interactions, that were investigated in each SES and are represented in a graph is a SPDF metro-map.

Balancing: where the knowledge from the previous steps converges and is integrated to effectively create the SPDF metro-maps. This step is composed of two subdivisions: (a) Reality check: To verify that each metro-map focuses on the variable of interest. The analysis includes comparing the summary of a "problem definition session" and a dispersion analysis with the main variables used in each metro map (Figure S1). This step is to ensure the variable of interest is the main issue each SES wants to address (i.e., the key challenge faced by each SES). (b) Revealing hierarchy, synergies, and serendipities: these steps require more description and are explained separately below. In short, they embrace the construction of the pathways' hierarchy and the identification of the additional traits used to populate the SPDF metro-maps.

SPDF metro-maps navigation: with the metro-maps ready this step represents the bull´s eye of Fig. 4, where amongst all possible options to manage the system, a reduced number of options are represented by each graph. We explored two forms of navigation of each metro-map: 1) single use navigation, based on worldviews; and 2) coordinated navigation based on the hierarchical relations between each pathway.

Rebuild the system map and restart the cycle: as users of SPDF perceive the system map does not capture a relevant understanding of the system causal connections anymore, proceed with a new group model building and restart the process.

Pathway metro-maps serendipities

Each pathway can be used to investigate additional traits related to each variable. These traits are not initially framed as the objective of each management action (they are indirectly related to the variable of interest); therefore, they are considered indirect gains (i.e., serendipities) of a governance process. In the present study, two sets of serendipities were tested: the SDGs and expert recommendations. The SDGs[46,70] were identified by the authors through recognition of the relevant SDGs that are directly affected by each variable in a pathway.

Expert recommendations were obtained during a subsequent in-person workshop, with approximately the same group of experts per DA from the first set of workshops. These experts were asked to distribute an "X" number of points to a preliminary version of their area´s metro-map. These points, collectively decided upon by each expert group, imbued some variables in each pathway that the group deemed more influential in their respective case, with the backdrop of leading the SES towards SSP1. To represent some scarcity (and coerce the participants to discuss their assumptions) "X" was defined as the total number of variables summed in each SPDF metro-map divided by 2 (i.e., Macaronesia had 11 points, Tuscany had 12 points, and the Arctic 9 points). The intensity of this recommendation varied from 1 to 3, reflecting the decisions made by the participants. Three independent observers provided comments from this workshop (Supplementary Material E) which can be used to improve the methods in the future.

Systemic Pathway graphs and hierarchy

Each SPDF metro-map was built using the Pathways Generator, version 2015, Deltares, Carthago Consultancy, and complemented in PowerPoint for the background colours, SDGs and scientific recommendation icons. The colours of the PESTLE elements are just illustrative and do not correlate with the background colours of each pathway (Table 2) that represent the hierarchy between pathways.

Our main assumption in this study is that the problem in each DA is influenced by a set of variables, and these variables do not occur in isolation in a vacuum: they form a system[6]. Furthermore, these variables influence/are influenced by each other at every moment, in such a way described by the CLDs, forming an SES. Therefore, when we step forward with the analysis and show linear chains of connection which start with arbitrarily selected PESTLE variables and end in the variable of interest (i.e., one systemic pathway), we are representing that the behaviour of our variable of interest depends on these pathways, and these pathways interact between them hierarchically. The next step, then, is to show how this hierarchy is manifest.

In this line, the pathways in these metro-maps were classified according to a hierarchical property they were attached to. As pathways can promote or be promoted by each other, this process can be used to see if independent management actions are converging or diverging toward the variable of interest. To coordinate independent efforts, it is strategic to prioritise variables that influence or enable variables of other pathways because they would benefit from their systemic connection, revealed by the causality between them (investigated previously and described by the CLDs). On the other hand, pathways that are disconnected from the others have a lesser influence on the whole system as they are not being systemically enabled by or are enablers of any other pathway. To make this hierarchy explicit in the metro-maps, a background colour was added to each pathway (Table 2).

Finally, lock-ins represent the lack of pathways, in other words, the absence of a causal connection between a PESTLE element to the variable of interest. They happen in two forms: first, there is no connection (i.e., no regular variables, no stepping stones) between a PESTLE variable and the variable of interest in the CLD of the system; second, the variable of interest is a PESTLE variable, and therefore there can be no pathway between "itself". In both cases, the result is the same, these disconnected variables can only be managed directly, not in a systemic way (i.e., a resistant variable), preventing the possibility of having a "complex set of interventions" influencing these variables[57]. In the SPDF metro-maps, lock-ins are shown as disconnected PESTLE variables on the left side of the figure, as they cannot reach the right side of the SPDF metro-map where the variable of interest is.

Navigating the Pathways

Individual choice is difficult to predict, therefore SPDF metro-maps reveal possibilities to influence the variable of interest, forming a set of options for unknown actors and policy-makers to systemically impact the variable of interest. To reduce the complexity of the social choice, we used a heuristic that simplifies the way people would prefer one pathway over another. We adopted the typology of worldviews from the theory of plural rationalities (aka Cultural theory)[34,41–43]. To this theory, four types of worldviews influence people's choices: (1) the individualist, a market-led efficient, fully informed decision-maker type; (2) the hierarchist, who understands that wise guidance from specialists, standards, and planning are the solution to all problems; (3) the egalitarian, who believes all social problems are interconnected, and that a precautionary approach regarding nature would provide society with the required stability in a fragile planet; and (4) the fatalist, which in most of the theory is not politically active and will be omitted here for the sake of simplicity (e.g., for this group the system where they live has no rhyme or reason, and their solution is to cope with the unpredictable changes). This heuristic is adequate as it was already used in the adaptive pathways literature[24,38], it is very congruent with the ideas of wicked problems[3,18] and was already considered regarding EBM issues e.g., see ref. 25.

Complementarily, independent actors trying to influence the variable of interest can be mapped using the SPDF metro-maps, promoting possible coordination of these actions. This coordination was explored here by analyzing a hierarchical connection between pathways of the same SPDF metro-map, revealing which combination would benefit most of the interdependences between them. We grounded this coordinated navigation with examples from each DA. The resulting strategy is not prescriptive but reveals systemically supported patterns arising from the hierarchy between the pathways.

Finally, trade-offs arise from the distinct choices on how to navigate the SPDF metro-maps. By single use navigating one pathway, the SDGs and scientific recommendations from the other pathways inside the same SPDF metro-map are ignored (i.e., a trade-off). When a determined action uses a certain pathway, the serendipities associated with this pathway can be promoted/demoted, but by ignoring other pathways, other serendipities associated with those pathways are not being affected, therefore representing trade-offs.

Data availability

All data used are in the supplementary materials, which are formed by the CLDs and descriptions of the modelling sessions and results.

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Author contributions

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Competing interests

The authors declare no competing interests.

Additional information

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