Musing on the concept of Good Environmental Status:

the complexity of the status & the status of complexity

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Table of Contents

Introduction

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Mankind is facing grand challenges to deal with the complexity of eco-socio-economic systems which entail a paradigmatic shift to a new way to design and tackle the process towards possible solutions: research and innovation can and will play a fundamental role in this regard.

The Good Environmental Status (GES) fostered by the European Union's Marine Strategy Framework Directive (MSFD) is one of these challenges, addressing a diversity and complexity of systems in terms of social, economic, environmental and political aspects, as well as, of the related stakeholders. Human activities and protection of the marine ecosystem have to be integrated in the concept of shared values, towards a sustainable and feasible economic and environmental framework.

To maximize the impact of investments and make the contribution of science relevant, the interface between science and policy is crucial to adopt efficient and effective interventions. In this context, the MSFD has provided a fundamental milestone towards the cooperation and integration of national efforts in addressing the Good Environmental Status of the marine environment, whose potential is still to be fully exploited.

Effective linkages are needed between emerging knowledge, innovative approaches and techniques in marine science and its practical understanding, and possible uses within the MSFD context. This means that criteria, including threshold values, methodological standards, and proper representation of the MSFD descriptors, should be periodically reviewed and amended in the light of scientific and technical progress.

The efficient mechanisms for such revisions should also be built and strengthened, including the development of new and innovative observational schemes and techniques, available for Member States. This will lead to a better consistency in the determination of the GES of different marine regions in the European Seas.

In such a context science can contribute revising or introducing criteria, apply risk-based approach, and provide rigorous definitions to sharpen and refine/specify the concept of thresholds and, in turn, of the Good Environmental Status. Science has also the responsibility to foster data harmonization and interoperability, as well as integrations among MSFD Descriptors.

The Joint Programme Initiative Healthy and Productive Seas and Oceans (JPI Oceans) is a pan-European intergovernmental strategic platform open to all EU Member States and Associated Countries. JPI Oceans coordinates and integrates research programmes for tackling marine and maritime challenges.

In November 2019, JPI Oceans launched the Joint Action "Science for Good Environmental Status (S4GES)" to better understand marine ecosystems, how multiple activities impact the environment and how to fulfill the requests of MSFD.

Together with BlueMed CSA - which is an intergovernmental initiative launched in 2014 during the Italian Presidency of the European Union, aiming to advance a shared vision for a more healthy, productive, resilient, better known and valued Mediterranean Sea – a 1st Expert Workshop was organized virtually from December 2-4, 2020. Experts from different countries around Europe and different expertise in assessing complex system came together to discuss:

- Which theories and methods will help us in dealing with complex systems and identifying a Good Environmental Status?
- How can knowledge drive decisions on the design of the appropriate (process-based) strategy to understand complex system dynamics?
- For the ocean domain, what can we learn from other disciplines (e.g. assessing human microbiome, forests, soil, and ecosystems in general)?
- What can we learn from existing approaches in the ocean domain?
- How to manage the MSFD framework and science-policy interface?
- What can we learn from other countries and how do we connect to each other?

The overall goal of the workshop was to address the scientific contributions to design and structure a complementary path in addressing the Good Environmental Status, where individual and official positions are asked to confront within a scientific and interdisciplinary approach. Participants can contribute to launch a 'small world network' for the identification of the most relevant theoretical and operational aspects and paths to be considered.

This Proceedings Paper showcases the different aspects and contributions of the workshop, in particular focusing on how science, governance and implementation can be integrated taking into account the state-of-the-art. In addition, recommendations for future considerations and activities within the JPI Oceans Joint Action on Science for Good Environmental Status are given.

Session I
Dealing with complex systems - concepts

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We all know that the world's major ecosystems have been affected by a rapid and intense deterioration. This has expectedly boosted environmental monitoring and the search and development of indicators of ecosystem health. Before it is too late, we have to act promptly and avert irreparable damage.

We all agree on that, but when can we state that an ecosystem, be it marine or terrestrial, is healthy? Is that something similar to human health? We need some criteria to adopt efficient and effective interventions.

The EU Marine Strategy Framework Directive (MSFD) is a fundamental milestone towards the integration of national efforts in tackling the problem of healthy marine environment. It provides "qualitative descriptors for good environmental status". 11 macro-descriptors have been put forward, which ought to highlight when a marine ecosystem works/functions appropriately (Biological diversity is maintained, Non-indigenous species are at levels that do not adversely alter the ecosystems, Human-induced eutrophication is minimised, Sea-floor integrity, …).

But how can we address the problem of defining health for ecosystems if we don't know how an ecosystem works, how it functions? The state of an ecosystem cannot be surmised simply by adding up the states of its individual parts. They are (complex) systems in which the constituent parts dynamically interact with each other, and because of such interactions some patterns emerge, patterns which cannot be understood at individual/organismal level, or simply by computing some plausible indicators.

Words like health, resilience, recovery, integrity, organisation, vigour will only be kind of buzzwords if we are not able to build up a theory of ecosystems. Mathematical or at least computational models can help us with this by telling us how they behave and how their properties emerge. Health may well be one of these emergent properties.

In recent years, some experts have started thinking that we do not need theories or models for assessing ecosystems health because we already have loads of empirical data which we can dig into. We can stop looking for models, we can analyse data, plug them into a black box, turn a handle (algorithm) and they will eventually tell us what we need to know. Like a modern Apollo's oracle at Delphi. This way of thinking has led some people believe that we just need to collect empirical data, analyse them, search for regularities and calculate indicators. This will tell us straight away about whether marine ecosystems are healthy or not.

However, H. Poincarè — one of the greatest mathematicians and physicists of the last century — back in 1901 warned us that "Sciences is built up of facts, as a house is with stones. But a collection of facts is no more a science than a heap of stones is a house." This is a crucial point, the quest for a "mathematical" theory of ecosystems. Data may contain artefacts and biases such as sampling effects, spurious correlations and finite-size effects - they need theory to be interpreted. Quantitative approaches can help us making informed predictions, can tell us what we may or may not expect from the empirical data. The talks of this first session are going to show how complex system approaches can help understanding what a healthy ecosystem may look like.

In this session, we hosted a series of talks which atold us how a complex systems approach can help understanding what a healthy ecosystem is.

Main outcomes of the session and its discussion are:

- Empirical data and history of systems per se are not enough to make reliable predictions. We need to identify the appropriate variables and find the effective equations which govern marine ecosystems. These models could help us predicting trajectories at large scales and hence identifying how un-perturbed time series will look like.

- Physics – more specifically, statistical mechanics -- provides us with model-independent approaches which can be used to identify general features of ecosystems. Also, theoretical models help us explaining patterns. Forest dynamics has already a range of successful examples which teach us that health in ecosystems is an emergent feature which can be quantified. This approach could be also applied to marine ecosystems to characterise their health on a more quantitative basis.

- Normative dimension of sustainability is a thorny issue. We have to outline how marine ecosystems should behave when they are healthy and for identifying this we currently have the indicators identified in the MSFD. However, it is difficult to place sustainability within a more general framework in which we include young and future generations; whether we ought to sustain a safe existence for human beings, or value species and ecosystems independently of their current relation with human beings.

- When dealing with different European stakeholders it is important to make them aware of the range of possible solutions which are at stake, without oversimplifications. All the actors involved in governance processes should identify solutions by sharing goals grounded on a common ethical basis. A complex systems approach should help integrating governance with society and ecosystems.

Understanding the dynamics of a complex system: theory, models and data

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Detecting patterns and recurrences in nature and using them to improve fitness is a capability of most, if not all, the living organisms. As far as we know, humankind is the only one that has developed specific constructs to analyze and classify the patterns in a quantitative way. It is likely during the Neolitic that systematic tools were developed and firstly formalized, but a crucial breakthrough was at the time of Renaissance and culminated with the synthesis by Isaac Newton's 'Principia' in which he formulated the laws of classical mechanics.

To some extent erroneously, that synthesis is considered the birth of the idea that nature obeys unchanging laws which can be formulated in mathematical language. This led scientists that continued the work of Newton, like Laplace, to state that by knowing all forces of nature and the initial conditions of all components it would have been possible to predict the future of the universe and also to reconstruct its past. Even at that time there were alternative views, e.g., the alchemists, but the prevailing view was that any natural process could be dissected in terms of mechanical sub-processes. In principle any process of which we know the evolution laws, even without the knowledge of why that laws work, should be predictable. Indeed, there are processes of which we know the evolution laws (e.g., astronomy), others for which there are evolution laws but we don't know them (e.g., earthquakes) and others we do not even know whether there exist evolution laws (e.g. finance, social phenomena). In a generalized Newtonian approach a system for which we know the relevant variables and the evolution law we may formulate the rules with differential equations as

$$\frac{d\mathbf{x}}{dt} = \mathbf{F}(\mathbf{x})$$

for which we may find analytical solutions and obtain nice formulas for the evolution in time of the system. In many cases finding the analytical solutions is not at all straightforward however there are methods, e.g. qualitative analysis and numerical computations, which allows for some predictions.

The scenario becomes less friendly when the system is chaotic or "complex". The word complex has been overworked in the recent decades but in this context a complex system is a system composed of many interacting parts and/or whose dynamics covers several spatio-temporal scales. Even an apparently simple system with two suns and one planet with just the gravitational force acting, may behave in a very intricate way (Fig. 1). Furthermore, even in the case of a strictly deterministic law, in presence of chaos, any prediction of future state of the system may be only approximate since the values of the variables that determine the evolution of the system will also be affected by some uncertainty and the initial uncertainty can produce very strong uncertaninty in the evolution of the system. This is frequently cited 'butterfly effect' which was discussed by Poincaré long before the introduction of the concept of 'Chaos'

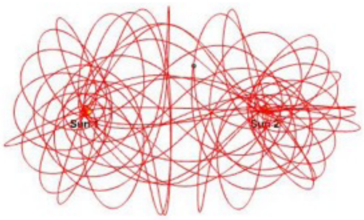

Figure 1: Trajectory of a planet attracted by two suns.

(Lorenz 1963; Lorenz 1995). The apparently simple model, with just 3 variables:

$$\frac{dx}{dt} = \sigma(y - x), \frac{dy}{dt} = -xz + rx - y, \frac{dz}{dt} = -bz + xy$$

displayed a "complex behaviour“ which prevented, even for a strictly deterministic system with a well defined evolution law, an accurate prediction of the future states of the system.

On the other hand, the exponential growth of available data on natural processes supported by an unprecedented increase of observational techniques and of data storage and processing power led C. Anderson to make the provocative statement that "*The data deluge makes the scientific method obsolete*" (Anderson 2008). The basic assumption behind this view is that from the same antecedents follow the same consequents. This is the method of analogs which assumes that if the system is deterministic, in order to understand the future it is enough to look to the past for an “analog“ i.e. a vector x_K with k<M such that $|\mathbf{x}_k - \mathbf{x}_M| < \mathbf{x}_k$ therefore, since “from the same antecedents follow the same consequent“, we can “predict“ the future at time

$$M + t > M:$$
$$\mathbf{x}_{M+t} \simeq \mathbf{x}_{k+t}$$

Lorenz himself tried to use meteorological charts of the past to perform weather forecast but, as also Lewis Fry Richardson has predicted, he never found in the available maps two *t* configurations fairly similar. Indeed there were grounds to assume that a deterministic systems, which occupies a bounded volume in the phase space, should return after a certain time to a previous state. This is the "Recurrence theorem“ of Poincaré (1890). However, already L. Boltzmann, in a famous dispute about irreversibility with E. Zermelo, showed that for systems with N degrees of freedom, the return time would be very large and would scale with the power of the number of components, i.e., $T_R \sim \tau_0 C^N$. where τ_0 is a characteristic time, C>1 and N is in the order of 10^{20}–10^{25} for a macroscopic system (Boltzmann 1896).

The intuition of Boltzmann has been formalized by the Kac Lemma (Kac 1959) which states that: "In an ergodic system the average return time at *(A) ñ> =t0\P(A)* where P(A) is the probability to be in A. This means that for systems with a large number of components the recurrence time may be much longer than the age of the universe.

Said that there is a limit to the accuracy of predictions we can make even for a deterministic system for which we know the evolution laws, and that we cannot rely on the principle of analogs for realistic systems, there is third aspect we must consider when trying to quantitatively describe the evolution of systems characterized by the presence of a variety of degrees of freedom with very different time scales.

L.F. Richardson, a pioneer of weather forecasting, dealt with this problem when he carried out his first attempts to forecast weather starting from the first principles, i.e., the equations of hydrodynamics, and considering their action at all the existing scales, from micro-turbulence to the large atmospheric gyres. His approach was, somehow, "reductionist“, meaning that he wanted to derive the macroscopic behaviour of the system looking at the first principles (Cecconi et al. 2012). The first Richardson’s results were very disappointing and it took some time to realize that the fully bottom up approach by Richardson was not the proper one. Indeed, the first step in approaching the analysis of a "complex“ system is to select which aspects are to be taken into account and which ones can be ignored. This had been stated even before by many, among which K. Gödel who wrote:

“To develop the skill of correct thinking is in the first place to learn what you have to disregard. In order to go on, you have to know what to leave out: this is the essence of effective thinking” (cited by Wang, 1997).

This was the approach followed by, e.g., Charney, Fjörtoft and Neumann (1950), which focused on the relevant processes and scales using what we can call the "effective equations" but also profiting of the significant improvement of computing machines that Richardson himself had envisioned. Fig. 2 shows all the scales characterizing the motion of geophysical fluids on the Earth.

There are not systematic methods to establish the effective equations, which typically often utilize variables of the system as a whole and in general formulate the evolution using only some of the variables. Let us stress that identifying the proper variables is a challenging task.

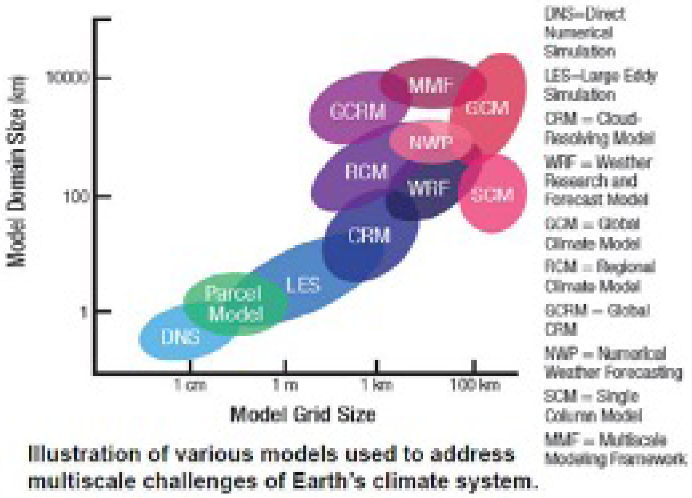

Figure 2: The range of scales in geophysical fluids and the models to simulate them.

In conclusion it can be said that:

- The idea (dream) to avoid the theory and use only data, is too naive. Because of the Kac's lemma, the BIG DATA approach can work only for very low dimensional systems.

- Old topics can be relevant even in modern practical issues: e.g. the Poincaré recurrence theorem (and Kac's lemma) for the analogs.

- It is true that the final laws of nature are not expressed in terms of mesoscale and frontal structures, however the unique way to understand the ocean is to write down effective equations for the mesoscale and frontal structures.

- The dream to build models just from data cannot work if the dimensionality of the problem if large enough (D>5 or 6).

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Sustainability as the balancing of ecological, societal, and economic concerns: an ethical perspective

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The concept of sustainability plays a central role in the MSFD context, where Good Environmental Status (GES) is defined as “that the different uses made of the marine resources are conducted at a sustainable level, ensuring their continuity for future generations.”1 In this text I explore what a sustainable use of marine resources means from the perspective of ethics. In other words: What are the key normative issues at stake when defining what a sustainable use of marine resources is?

2021 is the first year of the UN Decade of Ocean Science for Sustainable Development. This is a framework built on the recognition that securing healthy oceans are key to achieve the SDGs. In 2019, the IPCC released its Special Report on the Ocean and Cryosphere in a Changing Climate, confirming that we are heading towards catastrophic consequences if we are not able to put a break on climate change. By now we know a lot about climate change and how it may be mitigated, but there is also a lot we do not know, not least when it comes to how the ocean affects and will be affected by the changing climate on our planet. According to a report by the High-Level Panel for a Sustainable Ocean Economy (Hoegh-Guldberg et al., 2019), ocean based climate action can deliver up to 21% of the reduction in carbon emissions that we need to reach by 2050 in order to limit global temperature increase of 1,5 degrees Celsius, a reduction necessary to steer clear of the worst consequences. The reductions can be achieved among other things by increased production of ocean based renewable energy, greening of maritime transport, conservation of “blue ecosystems” such as seaweed and kept forests, a transfer to less CO_2 intensive seafood and the possibility to store carbon in the ocean floor (cf. Figure 3).

In other words, the ocean is recognized as key when we address climate change as well as other grand environmental challenges, such as threats towards biodiversity. On the one hand the ocean is seen as a vulnerable system that needs protection from human

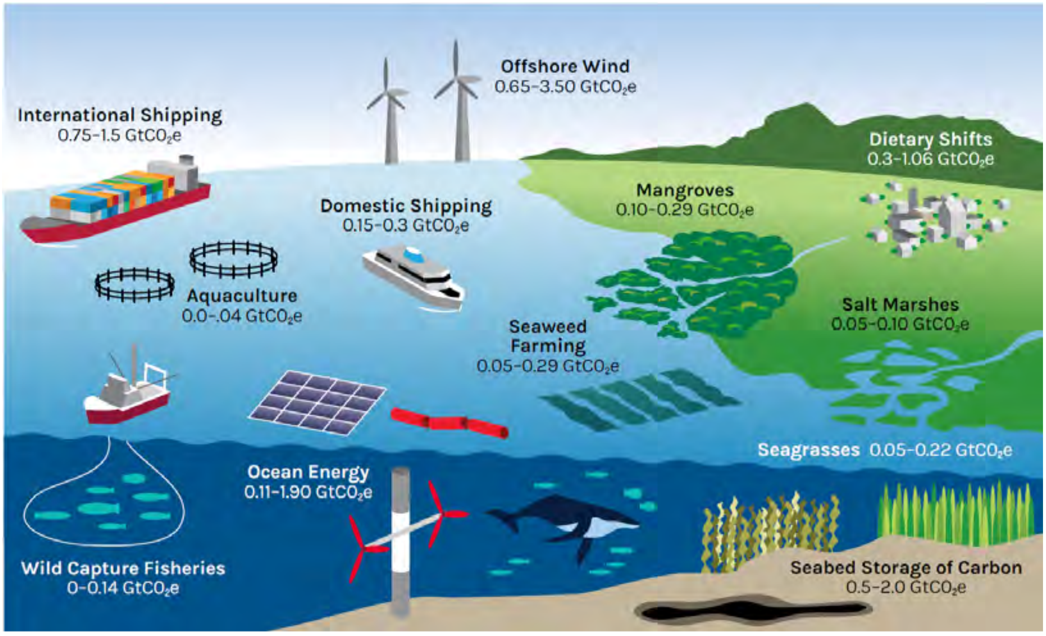

Figure 3: Ocean-based Mitigation Options, Hoegh-Guldberg. O., et al. 2019, p. 6.

over-exploitation, on the other hand it is increasingly presented as a solution to the very same challenges. The latter phenomenon has been referred to as "blue acceleration" (Jouffray et al.,2020), a concept illustrating how the ocean is increasingly presented as a solution to all our sustainability challenges. In this situation, it is vital to strive towards a holistic evaluation of the effects, and a cross-disciplinary as well as a cross-sectorial examination of the possibilities and limitations of these solutions.

Climate change is an example of a so-called "wicked problem" (Rittel & Webber, 1973) – it has even been described as a "super wicked problem" (Levin et al., 2012) because of how the complexity of the issue is repeated on multiple levels: Why is this happening? Who is responsible? What should be done? To achieve sustainable development in accordance with the SDGs is infinitely more complex, as the "wickedness" of SDG 13 (climate action), is echoed in the "wickedness" of most of the other goals, and SDG 14 (life under water) is no exception.

Thus, recognizing the complexity of sustainable development is an important starting point to understand what is at stake. The concept of sustainability was originally used in connection with environmental questions, referring to the use of renewable and non-renewable natural resources. However, in Our Common Future (1987), the report presented by the UN commission led by Gro Harlem Brundtland, a more complex concept of sustainable development was presented. The report outlined a development uniting two goals: Respect for the sustainability of nature and securing human values. Sustainable development was defined as "a development which meets today's needs without destroying the future generation's ability to satisfy their needs" – or, more poetically, that we should "treat the earth as if borrowed from our children, not inherited from our parents."

It is important to recognize that the concept of sustainable development is not a descriptive, but a normative concept – it is launched as an ideal of how development should be, what we ought to strive towards, and it is this ideal that is at the centre of the sustainable development goals launched by the UN in 2016. However, it is not clear exactly how this ideal can be explicated.

While Our Common Future arguably was framed in a neoclassical approach to environmental economics, where it is assumed that natural capital and human-made capital may be substituted for each other, a more radical interpretation has been suggested within the framework of ecological economics, where economy is seen as merely a sub-system of the more basic ecological system. Correspondingly, two normative conceptions of sustainability have been suggested: Weak sustainability, to which mainly neoclassical economists have appealed, and strong sustainability, which has been defended from within the tradition of ecological economics (Pelenc & Ballet,2015). Simply put, weak sustainable development is the view that environmentally harmful acts may be acceptable if they have great economic or social advantages. One may substitute one form of capital (environmental, social, economic) for another: The total capital is what is important. From this perspective, overfishing of particular species – although environmentally harmful – may be justified by the creation of both economic and social gains (e.g. employment). In contrast, strong sustainable development means that no economic or social gain can substitute some of the environmental "services" of the natural world: Climate regulation as well as biodiversity are examples of areas where no economic gain can justify irreversible damages.

Figure 4: A strong concept of sustainable development: The "wedding cake" model. Illustration: Azote for Stockholm Resilience Centre, Stockholm University (cf. Folke et al., 2016).

Although it was debated, the UN did not end up with an explicit endorsement of a strong concept of sustainability in the SDG framework. Explicating a strong over a weak concept of sustainable development could, however, strongly affect the policies chosen for a sustainable use of natural resources in the sense that certain SDGs would be prioritized over others.

Another normative question concerns the extent to which sustainable development should be understood as an anthropocentric concept. In other words: Is the world worth sustaining only for the sake of humans, or do other species or ecosystems count morally? In the environmental ethics literature, this issue has been formulated somewhat extremely as the Last Man Argument (cf. Routley 1973): "If you were the last person on earth, would it be ok if you trashed whatever is left of it?" The frameworks of weak and strong sustainability are both inherently anthropocentric. For example, Stockholm Resilience Centre's strong concept of planetary boundaries refers to boundaries within which humanity can continue to develop and thrive. Still, many have a strong intuition that ecosystems have a value independently of the existence of human beings. We may, however, assume that concrete policies will be affected more by the explicit framework we chose than by an underlying – and contradicting – intuition.

A third normative issue concerns the question to which extent we have moral obligations towards generations that come after us. As a starting point, this seems to be implied by the very concept of sustainability. However, from the perspective of legal or ethical theory, it may not be so straightforward to argue obligations towards someone who does not (yet) exist. The issue of intergenerational justice has been a source of controversy in the sustainability ethics literature, cf. e.g. Brian Barry (1997), who argued for "some notion of equal opportunity across generations", which would entail a protection of nature consistent with the provision of intergenerational equality of opportunity. Looking at how the SDGs are formulated in detail, however, the time perspective of the goals pursued are limited to 1-2 generations. We may ask to what extent the concrete frameworks and policies differs from our underlying intuitions of what we owe generations to come.

Brian Barry argued, as I have done in this text, that sustainability is a normative notion, which entails that disagreements over its meaning are disagreements about what should be sustained and for whom (Barry, 1997). Sustainability concerns the distribution of goods, rights, and disadvantages.

From the perspective of ethical theory, my recommendation for the Joint Action on S4GES would be to take into account that sustainable use of ocean resources means the balancing of conflicting interests, and that our normative assumptions regarding this concept have practical implications on marine governance issues.

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Governance of complex systems: are Homines Sapiens ready?

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Governance is a concept largely used in different contexts, and often abused. It mainly addresses the management of things and people via incentives and penalties, resulting in a multi-dimensional dynamic network of agents. Historically, humans have adopted hierarchical structures to guarantee control and prediction of the system. When dealing with complex challenges, control and prediction are rarely feasible and most of the organizational forms are inadequate to maintain the sustainability of the system and achieve the objectives. Some clues from different examples to manage complex systems will be here identified and analyzed: they suggest to focus on resiliency and self-organization when designing an effective governance structure. Unfortunately, humans are not inclined to adopt such approaches, which often implies circulation of roles and power. We propose to reflect on cognitive biases and misleading processes that entangle science and policy towards effective governance.

The ambiguity and vastness of the notion of governance

The word governance was used by Greek philosophers to describe the process of steering a warship. Its Latin counterparts are gubernare and regere, which were used both for steering a ship as well as the state. Governing has traditionally mainly associated to a mechanistic process.

Literature associates the concept of governance to a wide variety of different phenomena, from decision-making processes to policy instruments, addressing different institutional structures and actor constellations (Blatter 2012, Treib et al.2005, Young 2017). Literature on governance or organization of society, just limiting on social sciences, can show a number of articles larger than two millions. The ambiguity and vastness of the notion of governance, often with different terminology by different disciplines, may have contributed to its abundant popularity, and often to an abuse in many contexts. In a very simplified way, governance can be associated to the identification/design of "who does what", that is, to the structure and relations of roles. As we will briefly describe, it implies also the dynamics of the interactions and the reasoning of the action. That results in "who does what, when and why". Historically, the concept of governance has been associated to a hierarchical structure and mainly to the request of control of the system and prediction of its evolution. This is again a consequence of the mechanistic process which embedded the structuring of the governance, which in turn can be recognized in the Fordism introduced in the private sector at the beginning of the industrial era.

It is well-known that seas and the ocean address a complex system in terms of environmental aspects (Coles 2017, D'Alelio et al. 2019). Indeed, agents affecting this system involve many different stakeholders.

This interconnection of aspects usually requires a multi-level and multi-dimensional approach to governance, which has been also called "institutional cybernetics" (Kenis and Schneider 1991). Different approaches to manage the renewed complication of interaction between agents have been implemented, and in the European Union (EU), "network governance" is assumed dominant with respect to other forms as "statism", "pluralism" and "corporatism" (Eising and Kohler-Koch 1999).

Despite science has often been asked to support policy decisions and provide solutions to challenges, rarely science has been used to design the process for managing complex systems.

Many clues can be identified looking at the behavior of organisms, network science and private organizations. Governance of the marine challenges should therefore take advantage of the experiences from other disciplines than those traditionally associated to marine science and law. It is not only a matter of matching responsibilities within borders (trans-nationality) and fluid dynamics (problems with no borders), but a different affair.

The management of complex systems: from amoebae to markets

If we assume that the marine environment is complex, this does not imply that its management is complex too. In turn, the use of the adjective "complex" is very common in the last years, mainly referring to, or justifying, the lack of capacity to find sustainable and efficient solutions to the management of most of the marine challenges at local, regional, and global levels (i.e. pollution, raw materials exploitation, and fishery). Any of these challenges may involve and address many heterogeneous interacting parts, multiple scales, complicated laws, unpredicted emergence, sensitive dependence on boundary conditions (the past and the present, nowadays referred as the "evidence"), path-dependent dynamics, networked hierarchical connectivity, interaction of autonomous agents, non-equilibrium dynamics, deterministic chaos, synchronization, pattern formation, and criticality. The mentioned aspects are those that characterize a complex system (San Miguel et al. 2012) and many results in their investigations can constitute a powerful conceptual background now exported from physics to other disciplines (Badii and Politi 1999).

The characteristics of a complex system relevant to governance are:

- It cannot be linearized, that is, its properties cannot be predicted from the sum of its parts;
- It is difficult to predict its evolution with high accuracy in long-term timescales;
- It can show abrupt changes.

These aspects are strongly in contrast with the traditional approach to governance, which is focused on "control and prediction", and a mechanistic approach cannot be effective to guarantee the sustainability of the system. The experience can help, but relying on the evidence and on data can bring to misleading suggestions (Baldovin et al. 2018).

When dealing with complexity, it would be better therefore to look for models of organizations that have been developed and demonstrated to be competitive.

First of all, living organisms adopt organizational structures which have been selected by natural evolution. No leader cells exist in the amoebae (Kauffman et al. 1978): they assemble and dissemble without any programmed design to adapt to environmental conditions. Birds do not rely in chiefs, but they organize in storms to survive in migrations or against predators (Couzin et al. 2005). Self-organization seem to be the most effective form to manage complexity: it has been simulated by network science in explaining the emergence of "life" (Kauffman 2019). Self-organization does not mean anarchy, but often few rules can induce order in chaotic systems (Scholl and Schuster 2007, Boccaletti 2000).

Humans are primates, evolved in environmental conditions where events occur temporally as successive and localized in space. Globalization and hyper-connection have transformed the concept of space-time, towards "simultaneous and ubiquitous" events. Primates adopt "multi-level" societies (in family contexts, clans, etc.), and other mammals have less rigid boundaries between levels (Grueter et al. 2012).

Hierarchy, especially for humans, is mainly associated with a military organization. During World War II, the 6-day war, the invasion of Iraq, organizations other than hierarchical ones were adopted to deal with complex situations. Innovative organizational forms have been introduced by humans in response to the market dynamics (Lo and Zhang 2018, Atkinson and Moffat 2005, Dahlgren 2007). At the end of the story, any form of governance can be reduced to the study of the network of agents. In addressing the complexity of the recent society, we definitely face an increased awareness of the unstoppable power of leaderless organizations (Brafman and Beckstrom 2006, Laloux 2015, Coop 2013) and a lack of focus on addressing processes and languages (Gaucherel et al. 2012).

Reflections

Seas and the ocean address a complex environmental system. In addition, the management and planning of human activities, which impact on the marine environment, requires to involve a multitude of interconnected aspects. This management require the adoption of a governance, which can be theoretically structured as a multi-dimension multi-level network of dynamic agents (Moretti et al. 2021).

Governance has been historically associated to a mechanistic process and hierarchical structures, where control and prediction are considered the main requests for policy makers and authorities. Control and prediction increase in fact the chances to maintain roles and privileges at the top of the hierarchy. Complexity, for its nature, drastically reduce the capacity to control and predict the evolution of the systems. Different example of adaptation to manage complex systems can be identified to learn on how to "survive": these examples come from living organisms or from recent organizational structures. The ultimate goal of the organization of these systems is the sustainability of the whole system in its functioning, mainly adopting a self-organization bottom-up process.

Despite scientists have been asked to support policy in providing solutions to many challenges, rarely they have been asked to suggest the modes of governance that are the most appropriate for achieving the goals: the process has to be effective to make feasible the objectives.

Recently, resiliency is one of the concepts that are invoked to address complexity. In principle, it is true, since it requires flexibility and adaptation to the dynamics of the system. Has resiliency promoted to embed the governance too? The institutions, while promoting the involvement of stakeholders, consultations and introduction of success indicators for the objectives, seem to focus on robustness and not on resiliency. Robustness is the capacity to resist to external changes, maintaining the internal structure. Resiliency is the capacity to transform the organization/structure to adapt to the external changes, in such a way to still maintain the priority functioning. So, we can ask why we, as humans, are reluctant to copy, or at least to learn, from systems which show some kind of complexity and adopt strategies to maintain their functionality and identity. Many political scientists, anthropologist and psychologists, from Machiavelli to very recent experts, have described this behavior as the natural one for primates and to be affected by many cognitive biases (confirmation, anchoring, sunk costs etc.). Changes are not natural, "queens and kings" will protect their thrones, and any community can identify their own "thrones", that is their win-win situation. It is difficult therefore to convince policy-makers and scientists to abandon the current path: many investments have been spent and scientific publications are flourishing. The scientist in contingent sciences is in some sense "irreplaceable", as an artist is (Gaucherel 2019), and policy makers can advocate complexity as a justification for difficulty to find solutions, which are far to be adopted, or when suggested, are rarely feasible at global scale.

This being said, complexity does not address a formula to be solved mathematically, as well as for structuring a governance for complex challenges. No solution can be considered as a general effective one, but instead on focusing on communicating "what to do", it would be better to reflect on:

1) "Why is something not working?"

2) "Are assumptions compatible with objectives, and are the involved actors able, or willing, to provide impacting interventions in due time?"

3) "What cognitive biases are affecting the stakeholders

involved in the process?"

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Session II

Dealing with complex systems - methods

Gathering and handling Big data

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Recent advances in metagenomics have fostered a paradigm shift in the study of microbial ecosystems. These ecosystems are now analyzed by their genetic content, which makes it possible to highlight microbial composition in terms of taxonomy or, more recently, the biological functions that result from the functioning of these ecosystems. The fields of application are numerous. They have notably impacted our perception of living systems in the environment, such as the oceans' microbial composition or soils. They have also modified our perceptions of health since our intestines' contents are now scrutinized through the prism of microbial ecosystems whose emerging properties have a direct impact on humans and their health.

However, beyond the simple metagenomic description, understanding the interactions between communities or the emerging properties of an ecosystem remains an open scientific issue. Indeed, experimental data from ecosystems are heterogeneous because they are of different natures (i.e., discrete for genomic sequences, semi-quantitative for relative abundances of organisms, or quantitative for physicochemical data). Moreover, these same experimental data are often incomplete because they remain difficult to access despite recent technological developments. Finally, the ecosystems are installed in a substantial reference frame that covers a spectrum of gigantic magnitudes compared to other scientific disciplines (10^{-9} meters for a DNA molecule up to 10^{4} meters for the scale of an ocean), for which it is challenging to propose reductionist modeling without strongly degrading our representation of the systems.

Beyond computing power and data storage, computer science can meet these challenges with its ability to abstract data and systems. To achieve this, the authorization to direct research proposes to draw inspiration from computing techniques already implemented in cellular biological systems. Systems biology, a field of bioinformatics, is indeed confronted in some respects with the same problems. For instance, we can today assess a cell's phenotype from the expression of its genome; or inferring functional structure from the self-organization of molecules. Nevertheless, the application of systems biology at an environmental scale (or meta) is not direct. Indeed, the metagenomic description of ecosystems shows a large number of variables to be studied.

Moreover, communities are (i) complex and dynamical, (ii) described qualitatively, and (iii) the quantitative understanding of how communities interact with their environment remains incomplete and without real experimental capacities for exhaustive validation. Therefore, we must conduct computational efforts and implicit paradigm shifts to adapt systems biology approaches to ecosystem analysis and modeling. To do this, we propose to follow a now classical approach in systems biology, according to the tryptic (i) high-throughput biological data analysis, (ii) integration of data from the same system, and (iii) modeling of the identified system.

Considering that metagenomics techniques allow extracting the whole DNA or RNA that composes the ecosystem, and by focusing on ribosomal RNA or specific functional genes, one counts the number of copies that belong to a given species. An abundance matrix stores these count numbers where each line represents one Operational taxonomic unit (OTU), and each column a sample site where DNA or RNA has been extracted. For each OTU, one then shows if one is significantly over (or under) abundant when environmental constraints challenge the ecosystem. Whereas preliminary studies focus on describing the phylogenic distribution associated with this over or under abundance and how this diversity is related to environmental parameters, other studies propose to represent the abundance matrix as a graph – see Sunagawa et al. 2020 for review. Roughly, when two given OTUs show abundant patterns correlated (and above a significant statistical threshold), one links both OTUs in a graph. This graph, called a co-occurrence graph, is a weighted undirected graph where nodes are OTUs and edges represent significant correlations between them and weighted by a correlation score between the abundance signals associated with the two given OTUs. Herein, the most critical step of this technique is finding an appropriate threshold above which the absolute value of the correlation is significant. The methodological bottleneck is also herein using the accurate correlation-like metric for dealing with the data's compositionality. These graphs are the natural extension of standard data analysis in ecology and summarize the diversity of ecosystems and extract ecological properties. This same abstraction offers many avenues for comparing microbial ecosystems. However, behind this approach lies the problem (i) of dealing with large networks and (ii) linking the network with broader biological questions that are mostly associated with quantitative features. Indeed, the large number of edges makes challenging the standard functional analysis and the identification of keystone species without just describing them by their centrality in the co-occurrence network using state-of-the-art graph centrality metrics.

To overcome this problem and to integrate heterogeneous knowledge such as the genomic (semi-quantitative) and the environmental parameters (quantitative), we propose to apply a network analysis called WGCNA (Weighted Gene Correlation Network Analysis) that clusters the graph based on its overall topology. Compared to standard co-occurrence techniques, WGCNA builds a weighted graph and focuses on such an abstraction per se to perform the analysis. Thus, co-occurrence scores between nodes are weights allocated to corresponding edges. WGCNA aims to detect modules within the graph to emphasize a more substantial group of OTUs that present a strong correlation. For this purpose, weights from the weighted graph are magnified by a power-law function until the graph becomes scale-free. The graph is then decomposed into subnetworks (groups of OTUs) that are analyzed separately. One subnetwork (a group of OTUs) is considered interesting when its topology is related to a quantitative trait. Thus, for each subnetwork (for instance, the subnetwork related to carbon export), each OTU is spread within a feature space that plots each OTU based on its membership to the subnetwork (x-axis) and its correlation to the environmental trait of interest. The module eigenvalue estimates the membership. A suitable regression of all OTUs emphasizes the subnetwork topology's putative relationship and the quantitative trait. These modules are then considered trait-like because the more a given OTU is crucial to define the subnetwork topology (i.e., robust eigenvalue), the more correlated to the trait. Finally, to reduce the OTU number to investigate, we applied a Partial Least Squares Regression on each module associated with the carbon export. This technique computes a score for each OTU that belong to the module. The score then refers to variable importance in projection (VIP) and reflects a given OTU's relative predictive power. Higher scores emphasize the essential OTUs for the sake of prediction. OTUs with high VIP scores are necessary for the predictive model, as shown in Guidi et al. 2016 and illustrated by the figure enclosed.

Another way to deal with these extensive biological data consists of considering all genes as captured by metagenomic sequencing. By (almost) direct translation, one assumes the presence of a gene that encodes for an enzyme as a signal for the alleged use of a metabolic reaction within the organism. In particular, these computational techniques that use state-of-the-art gene databases help to identify, for a given organism, a catalog of catalytic proteins potentially produced by this organism. In the context of metabolism, metabolic reactions are feasible because of the catalyzer's presence, which allows the consumption of given compounds that will be transformed by the production of other ones. The checking of gene content represents a step called metabolic mapping. However, since the genetic information is highly incomplete despite substantial sequencing depth, and the chemical knowledge do not necessarily cover all biochemical reaction specificities in a given organism (in particular on the balance of co-factors), the sole metabolic mapping remains limited to characterize the full metabolic capability of an organism without further analysis. Modeling such a metabolic network can take either the form of a graph or a stoichiometric matrix. Whereas the graph implies the use of a discrete abstraction, the stoichiometric that resumes a network (i.e., flow between reactions) describes a set of constraints on integers, which then implies using a continuous abstraction. Different modeling paradigms are then possible. Constraint programming approaches allow reasoning in the space of constrained solutions. This space represents the domain of possibilities within an ecosystem under the hypothesis of satisfying mass action laws and quasi-stationarity assumptions. Within this space, it is then possible to estimate the flows of matter between the microbial strains present or explain the ecosystem's diversity according to the phenotypic behavior of each OTUs and under different environmental constraints. By relaxing the taxonomy constraints, such modeling estimates each metabolic reaction's importance for the implementation of broader processes such as biogeochemical processes.

The access to large datasets opens up numerous research perspectives to better understand the complexity of microbial ecosystems and holobionts in general. This perception and the underlying computational abstractions for the living, from genes to ecosystems, will be as many elements to consider to understand the impact of future disturbances on ecosystems fully. Computer Science's interest is to give herein access to several abstractions (from discrete to continuous via probabilistic ones). These abstractions are formal objects on which optimization techniques are performed, designed following parsimonious assumptions. These techniques thus aim at solving the original problem in an abstraction domain that becomes computationally tractable.

The most important recommendations for the Joint Action on S4GES are:

- Increasing the general sequencing effort of the global ocean. Several seminal data are available, but they mainly focus on ocean coverage. We advocate that we must increase our effort for time-series samplings and ocean processes studies. All these data will then be associated with standard environmental health status to understand better or identify new status.

- Maintaining a general metagenomics standard for automatic comparison of ocean provinces. The metagenomic data are not quantitative. Thus, more than others, we must encourage the use of similar molecular biology and sequencing protocol for data interoperability. It will foster the general use of the data and contribute to a general effort.

- Finding the proper abstraction for resuming the biological complexity. Graphs and networks are of first interest, but further works remain for incorporating these abstractions into general physical modeling of the ocean.

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Session III
Success Stories

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Evidence is not enough: Assessing a "Good Environmental Status" needs knowledge and science is therefore invoked to tackle the difficult task of disentangling facts from perceptions. Environmental dynamics and resources range multiple spatial and temporal scales, the "use" of ecosystem service and products spans a huge variety of social and economic sectors, the understanding of those relationships that link physical, biological, geochemical, and ecological stressors with actual effects and feedbacks is not a trivial task. Although technology has made advancements, we still lack knowledge on the underlying change dynamics and future impacts of them, at appropriate spatial and temporal scales.

What's the tool to monitor and assess all this? When dealing with environmental monitoring, sampling strategy demands a proper, processes-based definition of variables that need to be measured, methodological approaches, frequency and locations of the observations, thresholds, and visualization of the analyses. In such a context data alone are insufficient for understanding and predicting changes in ecosystem health. Successful stories show that data alone are insufficient for understanding and predicting changes in ecosystem health. Find a synthesis among theory, strategy and observation, in order to optimize the understanding of a physical process with an essential number of observables and/or indicators, is the efficient and effective strategy.

System vulnerability is assessed by evaluating the ability to meet specific targets and thus by extracting those effective processes that reduce the complexity of the system, allowing for suitable predictability. Ocean complexity, for instance, requires understanding effective environmental processes. Observing systems and methodologies need therefore to be planned by following a process-based design, aimed to solve the scientific challenges. In such a context it is worthwhile an upgrade that would introduce a breakthrough innovation in the sampling strategy.

The experts involved in this session showed how knowledge can drive decisions on the design of the appropriate (process-based) strategy. Specific challenges of holistic understanding in complex system dynamics, along with cross-disciplinary expertise, provide examples on actions that can set effective and efficient use of data and meta-data in describing healthy state and functioning of ecosystems, as well as adaptation and mitigation options.

Main outcomes of the session and discussion are:

From Thea van Rossum (EMBL, Germany) we explore the analogy between microbial community and ocean health in terms of those wrap-up indicators that may represent the status of the (eco)system. An interesting parallelism between human microbiome and marine community is that more than 90% of the system is unknown to us and we have no clue about the importance of this 90% on the health of these system. This increases the difficulty in the marine environment if we consider that the time scale of human diseases is reasonably short (years) while for time scales of the ocean environment can be much larger. Moreover, this contribution highlighted how a consistent and complete collection and storage of associated metadata remains a challenge. Despite this, a benefit of the meta-analysis of tens of thousands of samples is the opportunity to better describe the healthy state of the human microbiome, which has been revealed to contain much variability.

Maria José Sanz (Basque Centre for Climate Change, Spain) clearly explained that forests are complex, adoptive systems and they share several analogies with the ocean environment. The leading question is, therefore, how comparable forests and oceans are? In tackling this challenge, we need to consider that ecosystems are not only species communities. Moreover, spatial and temporal constraints might be different and this can be crucial when looking for analogies in restoration approaches. A further parallelism is on the quantitative assessment of the impact of climate change and the one from human treatments. In all these issues, for both environments, we need to set strategies for effective and efficient solutions. Actions to mitigate climate change are rarely evaluated in relation to their impact on adaptation, sustainable development goals, and trade-offs with food security. Some of the most promising adaptation options for land and ecosystems include mitigation options. This will require the understanding that they are complex systems that also respond to climate change themselves.

Grazia Masciandaro (CNR-IRET, Italy) highlighted analogies between soil and ocean in terms of ecosystem services and provisioning of products. Soil is a complex system, which provides a wide range of ecosystem goods and services that support ecosystem functioning and human well-being. In view of the remarkably complex biological, chemical and physical constitution of soil, it is evident the necessity and urgency of cross-disciplinary expertise for improved understanding of soil system health and functioning. Healthy soil and biodiversity, and also ecosystem services, have a great connection with MSFD. For MSFD the first descriptor, Biodiversity, is an integral of the system. Soil science seems to give great importance in biodiversity, considering it as a wrap-up indicator for the status of the environment, in a way to simplify the complexity.

Cédric Gaucherel (AMAP Laboratory, France) gave us the rare opportunity to discuss on the differences between a physical system and an ecological system, in particular, when dealing with process-based modeling. This contribution showed new methods that better reflects the properties of ecosystems, especially complex, historical non-ergodic systems, to which physical concepts are not well suited. The state space computed by these kinds of discrete ecosystem models provides a relevant concept for a holistic understanding of the dynamics of an ecosystem and its above-mentioned properties.

The Human Microbiome: success stories and challenges

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The bacteria, viruses, and micro-eukaryotes that live in and on us are critical to our health. Their presence not only can cause disease but can also be required to maintain good health. After a dozen years of human microbiome research, the field has yielded important successes but significant challenges remain. Early work focused on gut bacteria sampled from faeces using observational surveys. In many of these studies, the aim was to identify associations between microbial community members and disease states, with the major end goal to develop diagnostic biomarkers. In some cases, this has produced actionable outcomes, such as diagnostics for colorectal cancer, in many other cases, it has not. This can be due to many factors, such as a misprediction of the role of the microbiome, inadequately considered confounding factors, or using sample sizes that are too small to account for biological variability. To satisfy the requirement for large sample sizes, meta-analysis of shared public data has proven indispensable. This has been supported by centralised databases for microbiome DNA sequencing data and by studies revealing the importance of specific experimental steps. However, the consistent and complete collection and storage of associated metadata remains a challenge. Despite this, a benefit of the meta-analysis of tens of thousands of samples is the opportunity to better describe the healthy state of the human microbiome, which has been revealed to contain much variability.

Translating these descriptions of healthy states into usage in disease studies has been challenging due to population and individual level differences and variability in the effective definition of health based on the disease context. Human microbiome research has had great successes from studying health at the population level. This work will surely continue, but it has also opened up opportunities to consider personalised medicine approaches in the future and to consider health more specifically.

Comparing the human microbiome with environmental health – especially the ocean and its coasts – following lessons can be learnt for assessing the Good Environmental Status:

- Assess specific health measures which can then be summarized to overall health assessments. It is easier to define assessments for specific definitions of 'unhealthiness'.

- Consider impacts to human health as potential measure of environmental health. For example, (how) does poor soil health impact nutrition?

- When collecting data, ensure that it is measured, stored and shared in such a way that enables easy integration across studies.

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The soil and cognitive control

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Soil is a complex system which provides a wide range of ecosystem goods and services that support ecosystem functioning and human well-being. The cognitive processes involved in the relationship between man and soil go from perception to learning. Man's perception of the soil evolved in relation to his cognitive and technological development. The conscious man-soil relationship passed from the perception of the soil as a source of products necessary for food (agricultural conception) to the recognition of establishing a balance in the coexistence between man and soil, to the knowledge of the limits of the soil as a non-renewable resource (environmental conception). This is the perception of the soil as a vital substrate that works but also needs rest. In this context, it is necessary to learn to know the limits of the soil beyond which degradation situations could happen. The main soil mark is the fertility which provides us with nutritious food and other products as well as with clean water and flourishing habitats for biodiversity. In order to have healthy food it is necessary to have healthy soil.

The European Commission in the "Soil Mission 2020", in line with the Sustainable Development Goals and the Green Deal, defined the soil health as ”the continued capacity of soils to support ecosystem services”. In particular, soil biodiversity provides a range of different ecosystem services such as keeping disease-causing organisms in check, recycling and storing nutrients and making them available to plants, allowing healthy root growth, and providing a highway for air and water to pass through. In addition, soil biological community composition and activity, strictly interacting with physical-chemical structure, indirectly governs soil resistance and resilience. For this reason, the more diverse the soil foodweb, the healthier the soil ecosystem.
In view of the remarkably complex biological, chemical and physical constitution of soil, it is evident the necessity and urgency of cross-disciplinary expertise for improved understanding of soil system health and functioning.

"By 2030, at least 75% of soils in each EU Member State are healthy, or show a significant improvement towards meeting accepted thresholds of indicators, to support ecosystem services.": this is the main goal of the proposed "Soil Mission 2020".

Soil complexity

Soil is a multiphase mixture of minerals, water, air, and organisms, together with products of their transformation and degradation. Depending on interactions between physical structure, interface phenomena, soil biota activity, population dynamics, chemical composition, time, and environmental conditions widely differing types of soil can be formed.

Soils are characterized by a high degree of spatial structuring; they are composed of micro-aggregates, which bind soil organic carbon and protect it from removal by erosion, and of macro-aggregates, which limit oxygen diffusion and regulate water flow; each of the aggregates provides a unique ecological niche with its characteristic microbiome structure. In soil ecosystem, the biotic and abiotic processes and the connected interactions have strong impact on the microbial activity, supporting many central processes in soil. Microbial communities as well as other organisms which reside in soil are extremely complex and diverse; millions of species and billions of individual organisms can be found in various soils.

Monitoring soil complexity

A set of sensitive soil attributes that reflect the capacity of a soil to function can be used as indicators of soil complexity. The main soil properties or indicators for screening soil quality and health include: physical properties, expressed by structure, texture, infiltration, bulk density, water holding capacity; agro-chemical properties, expressed by soil organic matter (SOM), pH, electric conductivity, available nutrients; and biological properties, expressed by microbial diversity and functions (enzymatic activities, microbial activity).

Physical and chemical soil properties are very important for sustaining plant growth and biological activity. In particular, SOM, which plays an important role in providing energy, substrates, and biological diversity necessary to sustain numerous soil ecosystem functions, it is one of the most important factors when describing soil quality and fertility.

The SOM consists of chemical components differing in biological degradability: (i) rapid and medium turnover fractions, and (ii) more recalcitrant forms (humic substances) that turn over slowly. The former provides immediate and short-term sources of carbon substrate for the soil biota and contribute more to nutrient cycling; the latter, on the other hand, represents a long-term reservoir of energy that serves to sustain the system in the longer term and they improve soil structure. In order to understand the temporal dynamics of SOM in managed systems, it is therefore vital to characterize soil organic carbon quantity and quality. In particular, by providing nutrients and physical protection for enzymes and microorganisms, soil humic substance has widely been recognized as an important fraction of SOM that can be used to study soil ecosystem quality. Humic substances are able to bind extracellular enzymes and, preserving them from proteolysis and chemical degradation, might reflect the potential for soil resilience (Masciandaro et al., 2018).

SOM cycling is relied on soil microorganisms. In view of this, biological parameters, such as microbial activities, biomass, and community structure, have also been considered sensitive essential indicators to monitor soil quality and health. They change more rapidly in response to natural and anthropogenic factors with respect to physical and chemical soil properties.

Usually, enzyme activities are positively correlated to soil organic C contents and they have widely used in assessing significant changes caused on soil ecosystems by external pressures (Doni et al., 2017). Recently, developments in molecular-biology based techniques have led to rapid and accurate strategies for monitoring, discovery and identification of bacteria and their activities in the complex soil ecosystem. In particular, the combination of metagenomics, metatranscriptomisc, and metaproteomics may provide the link between microbial community composition and soil function (Karlen et al., 2019).

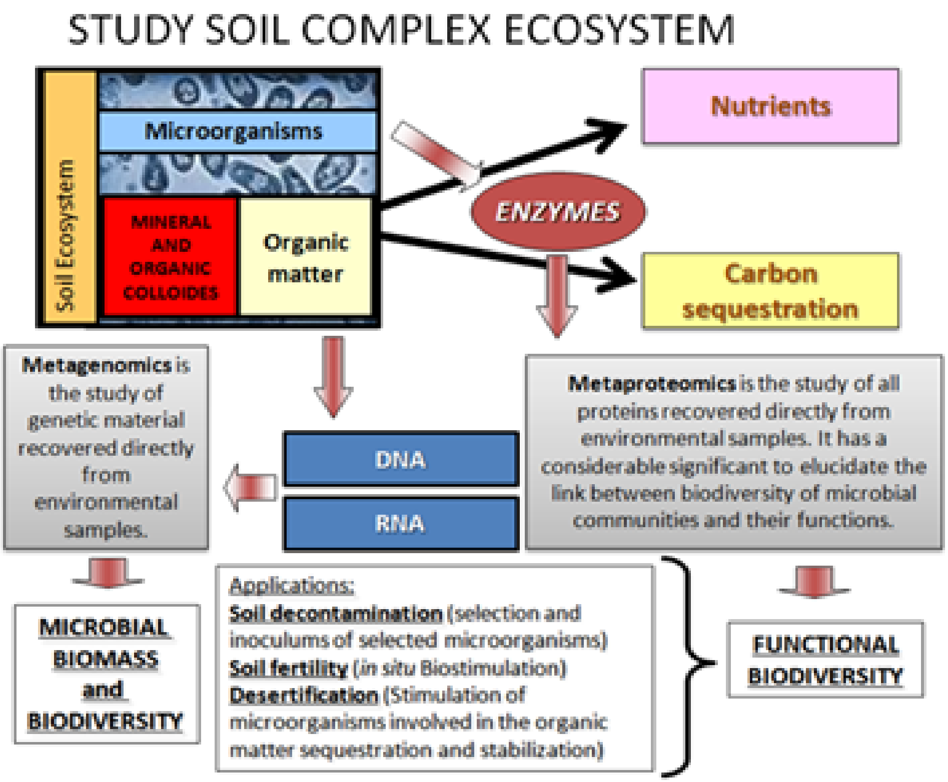

Figure 5: Masciandro (2020)

Healthy Soils for Healthy Life

Soils contribute to ecosystem services, such as agricultural production, carbon sequestration, recreational usage, and biodiversity. In particular, SOM and biodiversity preservation are very important objectives of the UN Sustainable Development Goals (SDG) and, more recently, of the EU Green Deal (EGD), as well documented in agricultural policy (Farm to Fork strategy), environmental protection strategy (Biodiversity strategy) and climate change mitigation (Climate Law). To achieve these important goals of the European Green Deal (EGD), there is the need to implement measures to preserve soil quality and limit soil contamination. Healthy food from healthy soils is one of the objectives of the Farm to Fork strategy and should be one of the slogans of the EGD. Unfortunately, many people do not understand or appreciate soil's critical support of life on Earth or how long it takes for soil to recover and renew after depletion. Damaged ecosystems are more fragile, and have a limited capacity to deal with extreme events and new diseases. Well-balanced ecosystems, by contrast, protect us against unforeseen disasters and, when we use them in a sustainable manner, they offer many of the best solutions to urgent challenges.

Comparing soil health with the environmental health of ocean and its coasts following lessons can be learnt for assessing the Good Environmental Status:

- There is the necessity and urgency of cross-disciplinary expertise for the development of reliable indicators of soil health, which combine all the different aspects of soil complexity and allow accurate comparisons. The lack of awareness of the importance of soil health in society further enhances the problem of soil degradation and fertility loss. Soil cognitive control should be based on a paradigm shift: from the traditional more static to a dynamic approach in which the soil is no more considered a stock to be exploited, but as a precious living organism to be cared for.

- Although widely accepted reference sets of indicators, reference ecosystems and standardized sampling protocols are missing, the application of accurate and sensitive indicators of soil quality and health, such as SOM quality and quantity, and soil biodiversity, have great potential in understanding the main processes occurring in soil. In particular, the use of novel molecular tools ("omics" approaches) can allow a functional characterization of the metabolic dynamics between and within species in the complex soil ecosystem.

- SOM and Soil Biodiversity, being key factors of important soil functions affecting soil resilience and ultimately the overall soil health, can be considered fundamental to link soil ecosystem services to human health.

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Characterizing integrated ecosystems: Understanding the complexity via application of a process-based state space rather than a potential

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Ecosystems are complex objects, simultaneously combining biotic, abiotic, and human components and processes. Ecologists still struggle to understand ecosystems, and one main method for achieving an understanding consists in computing potential surfaces based on physical dynamical systems (Scheffer et al. 2015). We argue that the foundations of this analogy between physical and ecological systems are inappropriate, and aim to propose a new method that better reflects the properties of ecosystems, especially complex, historical and non-ergodic systems, to which physical concepts are not well suited (Gaucherel 2019, Gaucherel et al. 2020).

As an alternative proposition, we have developed rigorous possibilistic, process-based models inspired by the discrete-event systems found in computer science, and produced a panel of outputs and tools to analyze the system dynamics under examination (Gaucherel and Pommereau 2019). The state space computed by these kinds of discrete ecosystem models provides a relevant concept for a holistic understanding of the dynamics of an ecosystem and its above-mentioned properties. Taking as a specific example an ecosystem simplified to its process interaction network (namely, a termite colony development), we show here how to proceed and why a state space is more appropriate than a corresponding potential surface.

Discussions during this workshop were stimulating and fruitful. Here are some points we raised from these discussions about the good environmental status assessment:

From a theoretical point of view, it appears critical for us to remind that ecosystems are not behaving as physical systems do. They are not behaving as purely biological systems either. Ecological and sociological systems have specific properties which many studies including ours are trying to identify. In particular living systems, or almost living systems as certainly ecosystems are, have a historical trajectory which physical model struggle to grasp (due to their frequent time reversibility). This is one central reason why we – nowadays - develop models inspired from theoretical computer sciences, and in particular possibilistic models.

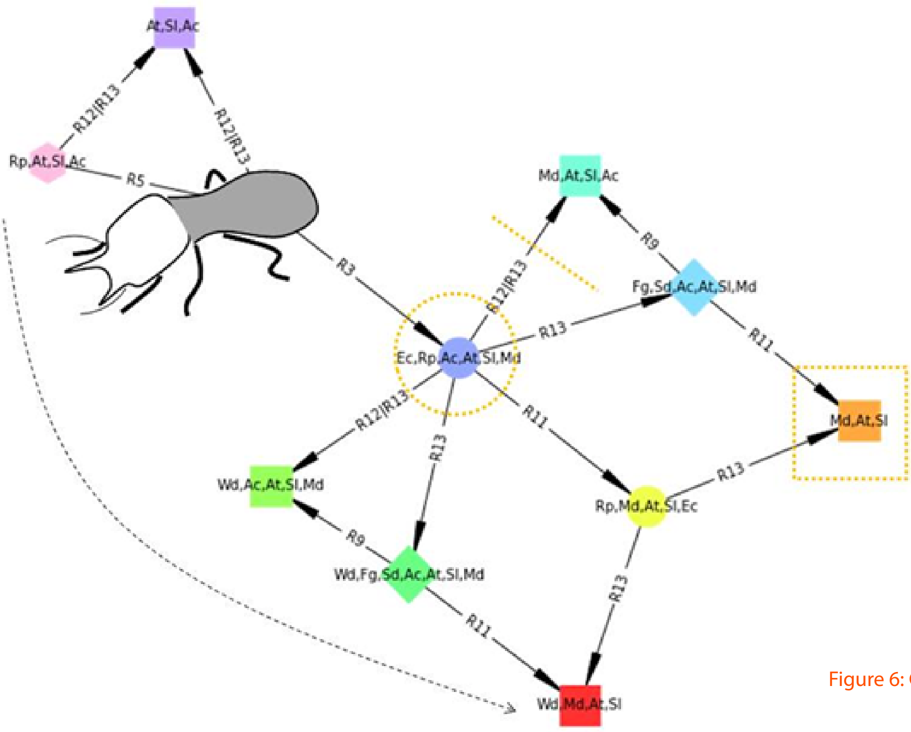

Figure 6: Gaucherel

Discrete-event models are well appropriate to grasp historical pathways and bifurcations of complex systems.

On a practical point of view, we already develop qualitative and discrete-event models which are aiming to assess the environmental status of social-ecological systems allowing us to manage these systems even though the systems differ in their complexity. We start by listing the relevant ecosystem components for the studied question, and then identify all processes these components are involved in. This builds what we call the ecosystem network, the "skeleton" of this system and of its model. By choosing a specific initial state of the system, it is then possible to compute all possible trajectories of the studied system with the qualitative and discrete-event model. This results in the identification of sustainable as well as dangerous trajectories. Finally, we are able to assess the environmental status of the system and to recommend decision makers or any other stakeholders on how to best manage the system.

This approach is already identified as being useful in many contrasted socio-ecosystems, such as temperate and tropical, terrestrial and aquatic, anthropogenic or non-anthropogenic ecosystems (e.g. Cosme et al., 2021). We are presently developing generic queries we may ask to such ecosystem models for helping assessing not only the status, but also the processes to fire and to avoid for improving the whole system status.

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Session IV
The ocean domain

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The Ocean is an essential part of the Earth system and a provider of resources, opportunities, goods, wealth and services allowing life on Earth. The expected increase in the world's population calls for additional food, energy, living and non-living resources and many more services and opportunities coming from the Ocean. Given this central role, the UN Sustainable Development Goals recognize the Ocean as a major driver for global systems that make the Earth habitable for humankind (Ocean Decade; 2021-2030). However, the Ocean is facing increasing pressures directly connected to increasing human activities with major negative impacts including climate change, ocean acidification, pollution, habitat degradation and species extinction (IPCC 2019, IPBS 2019). Hence, we need to explore and understand the functioning of the system on as many levels and details as possible to protect and sustain the healthy functioning of ocean ecosystem for the future of humanity.

Marine biodiversity and integrated ecosystem assessments

The role of species diversity and the dynamics of the complex interactions in marine ecosystems are major knowledge gaps for the assessment and prediction of Ocean's dynamics under present and future pressures. A limited number of biogeochemical elements can fuel the huge diversity of marine organisms, supporting major ecosystem functions and services. This huge diversity has been generally considered as a paradox in all aquatic systems, but we now know that the strong environmental gradients, the complex life history traits and trophic interactions, and three-dimensional nature of the oceans allow for the diversity of life forms to be develop and maintained (e.g. Chust et al. 2017). Nonetheless, pressures acting across scales can have large impacts on marine biodiversity, harming resilience and putting some of those functions and services at risk. Hence, present initiatives towards the restoration of functional, compositional and structural biodiversity at different organizational levels, should include the management of those impacts. The Good Environmental Status of our oceans can be then achieved within an improved understanding of the socio-ecological non-linear interactions in marine ecosystems which can enable moving towards a systemic framework for ecosystem assessments.

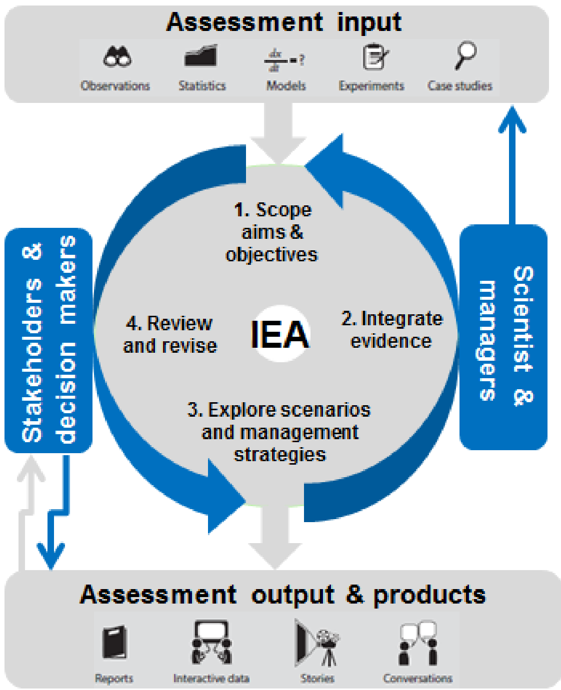

Figure 7: A schematic representation of modern integrated assessment frameworks used within climate and environmental impact assessments here adapted to fit the context of IEAs. Integrated assessment frameworks build on an iterative process where expert together with a broad range of stakeholders (involving decision makers and resource managers) assess the state and status of ecosystems by integrating the best available knowledge ackowleddging associate uncertainties (e.g. observations, modelling outputs and experiments) through a combination of qualitative (expert judgement based) and quantitative approaches. Potential future scenarios, risks and management strategies are also explored and evaluated. The process is periodically reviEwEd and revised as new data and knowledge become available. The output of such assessments is variable fitting the needs of multiple end-users. Redrawn from Mach & Field, 2017.

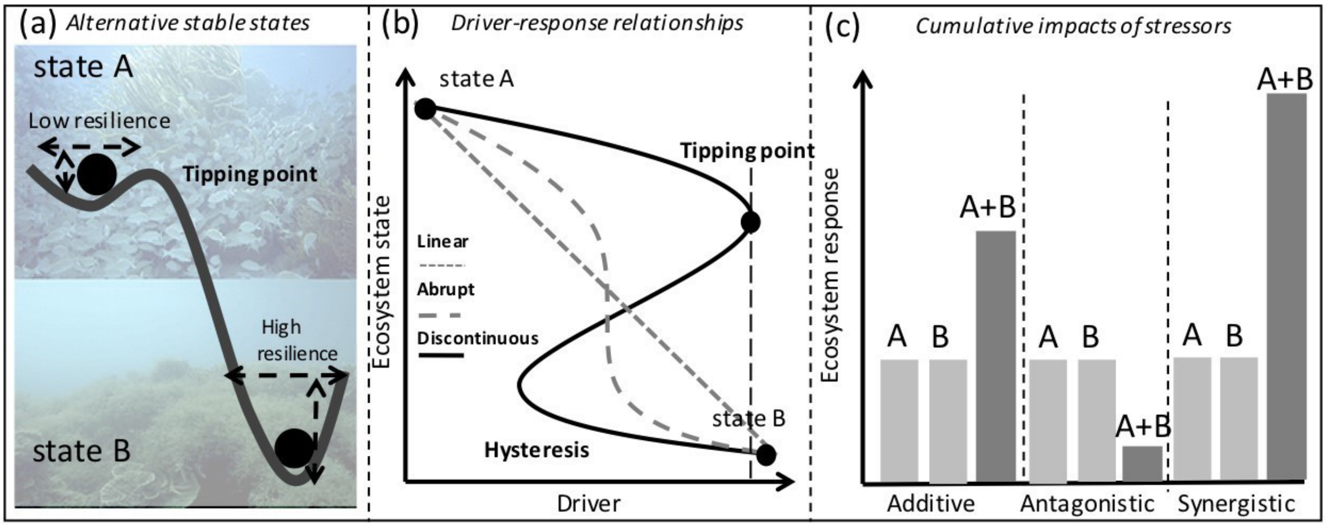

Figure 8: (a) Conceptual representation of regime shifts, involving abrupt transitions between two alternative ecosystem states (i.e. state A & state B) illustrated with a stability landscape (solid line) containing two basins of attraction with different degree of resilience to perturbations (i.e. in terms of the width and depth of the basin). (b) Examples of driver-response relationships where transition between states are typically characterized as either linear, nonlinear or discontinuous. (c) Example of ecosystem responses to cumulative impacts arising from interactions between stressors.

A systemic framework able to address direct and indirect pressure effects on ecosystem components should account for the full range of socio-ecological interactions moving towards the implementation of ecosystem-based management strategies (EBM) in the marine ecosystems. Presently, it is considered that Integrated Ecosystem Assessments (IEAs) represent the best strategy towards implementing marine EBM (Levin et al 2009). IEAs go beyond observing system states. They are means towards evaluating the status of knowledge on complex problems relevant to society. These assessments are experts review of evidence needed for decision-making, including consideration of trade-offs between different uses and ecosystem services. Such analyses require a suite of methods that range from qualitative (e.g. in data poor situations) to quantitative complex modelling approaches to fully account for the many sectors and components comprising ecosystems and to assess them in combination and not in isolation. Methods and tools developed in complex system theory and big data analyses could contribute to gain insight into these dynamics.

Behaviour, resilience and adaptation in marine ecosystems

Ecosystems, the services they provide, and the people who use and manage them, comprise complex adaptive systems which may exist in different alternative states, differing markedly in terms of their structure and functioning. Abrupt transition between such states, often termed regime shifts, are typically characterized as either linear, nonlinear or discontinuous, resembling fundamentally different types of ecosystem responses to external drivers (Scheffer et al 2001, Scheffer & van Nes 2018).
While all three types of responses can give rise to abrupt changes in the biota, only the latter involves hysteresis which indicates that irreversible changes in the structure and functioning of ecosystems may occur. The underlying mechanisms behind such shifts are such that while some drivers primarily serve to weaken the resilience of the system (Folke et al 2004), sudden perturbations from other drivers may trigger the actual shift, once passing beyond a tipping point. Despite a strong theoretical foundation of non-linear system responses to cumulative impacts, and our ability to map and identify abrupt ecosystem state changes from historical data (Blenckner et al 2015), our understanding of the underlying mechanisms and drivers of regime shifts, their interactions and cumulative impacts on the status and resilience of ecosystems is largely lacking (Fig. 8).

A central question in this context is how different levels of biological organization interact to shape each other's function and system properties such as resilience to perturbations. One topic that has attracted particular attention is the role of individual behavior in shaping group- and population-level characteristics (Mariani et al 2013). Individual behaviour can rapidly change to local environmental conditions resulting in positive and negative feedbacks on the entire food web. This is true at across the entire range of ecosystem components and from microorganisms, to plankton, fish and mammals. Less is known, however, about the influence of collective behaviours on ecological processes such as the ability of populations / species / traits to disperse or invade new habitats. Behavioural as well as other physical, biological and evolutionary processes regulate ecosystem functioning at different temporal and spatial scales. A central challenge in ecology is the integration of these processes in models or experiments that can faithfully describe the mechanisms underpinning the interactions between those scales.

Ocean migrations and collective dynamics

Complex system dynamics are largely affected by interactions with other systems and this is specifically relevant in marine ecosystems since the ocean has no boundaries. Marine species are potentially important and highly mobile agents affecting the functional and taxonomic diversity of food webs in different areas and times of the year, as well as the transfer among regions (e.g., trans-Atlantic east-west or north-south) of energy, biomass, nutrients and pathogens. However, for most megafauna species, their provisioning of ecosystem services is unclear and in particular the role of their migratory behaviour for ocean ecosystem functioning and biodiversity maintenance. Similarly, is it largely unknown how sensitive their migratory behaviour and other life history strategies are to changing ocean conditions (e.g. temperatures, oxygen conditions, currents, stratification), human pressures (e.g. overfishing, disturbance, pollutants incl. noise, hormonal disruptors and chemical substances) and e.g. naturally occurring outbreaks of diseases. These knowledge gaps thus pose a significant challenge for the operationalisation of ecosystem-based management of marine stocks. New data and new knowledge is needed to improve the ability to manage marine resources at sustainable levels and to enable a healthy and resilient ocean supporting a healthy human society.

The individual behavioural traits regulating the ability of marine organisms to migrate are largely unknown, but are most likely resulting from the balance between individual preferences and collective decisions processes (De Luca et al. 2014). Migrations between widely separated but geographically stable locations of spawning and feeding sites raise several questions about how marine animals manage to learn and remember these often-complex migration routes. Where is the information on the path stored? How is it retrieved, shared and elaborated by a migrating group? Are the tasks significantly better when performed by the group than by isolated individuals? Examples of such a complex decision-making problem can be found in the structure of the migration routes of several species of crustaceans (e.g. crabs), fish (e.g. tunas, mackerels) and marine mammals (e.g. cetaceans).

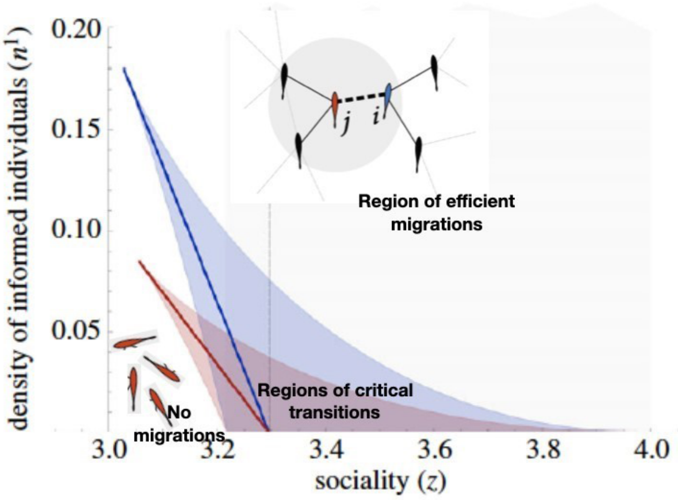

Figure 9: School of tuna (left panel) and mechanisms for group formation and migration in fish schools (after De Luca et al 2014). Modelling individual preferences and evolution of migratory behaviour, a group-level processes could be identified e.g. the collective memory of migrations. When the strength of collective memory is deteriorated (e.g. overfishing, feeding habitat degradation, etc.) the migration processes could suddenly stop because individual preferences will dominate over collective processes.

The increase in the amount of data collected at sea should go hand-in-hand with an equal increase in information and knowledge on critical marine processes that have been historically overlooked for the lack of accurate observations. The role of social information transfer and group dynamics in fish communities is a major knowledge gap in marine ecology, although it might have important implications in spatial and temporal distributions of the species (e.g. schooling, migrations, fear ecology) and have effects on functional responses between predator and prey.

The functional role and behaviour of several marine highly migratory species is unknown. This includes large groups of marine mammals (e.g., whales, dolphins, and seals), fishes (e.g., large tunas, sharks and rays), reptiles (e.g., sea turtles) and seabirds. Many populations are still impacted by both historical and present human exploitation for food, fuel and fashion, leading to low abundances. Most species occupy higher trophic levels in food webs and play important roles via (direct and indirect) cascading effects on the biomasses of lower trophic level species, thus controlling flows of energy, carbon and nutrients through the food webs.

Main outcomes of the session and its discussion are:

New knowledge should be developed to address:

1) the central role of species diversity in the functioning of marine ecosystems to support management tools resolving direct and indirect effects of increasing pressures;

2) the role of species' adaptation and behavioural changes to regulate ecosystem resilience under multiple pressures;

3) population connectivity at large ocean scales including the mechanisms of habitat selection and species migrations.

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The bottom-up view of marine ecosystems

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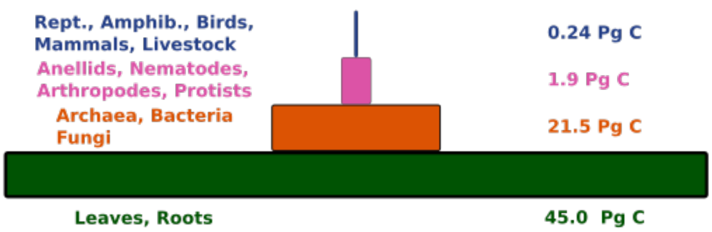
Among the different definitions of Ecology and, implicitly, of ecosystems that have been introduced since its first use in modern times by Haeckel (1866) the most common considers the ensemble of organisms and environment, with a particular focus on all the interactions among the different components, either biotic or abiotic (Margalef, 1982; Frontier et al, 2008). Within this conceptual framework, analysis of ecosystems may address the components (composition and context), the interactions (the structure), the fluxes among the components (energy or information) or all of them and their change in time (dynamics). Since ecosystems function at expenses of a flux and dissipation of energy through the different components (Margalef, 1968) a recurrent approach is the characterization of matter flow within the organisms, which is the structure of the so called food chains or webs, which link fluxes and structure with composition.

Elton (1927) analyzing the relative abundance of organisms with different roles within the ecosystem, extracted a general pattern, observing that:
'..a) smaller animals are preyed upon usually by larger animals, and b) small animals can increase faster than large ones, and so are able to support the latter...' which led him to propose that a 'pyramid of numbers' could be a good representation on the macro-structure of organism distribution within an ecosystem.

A few years later Lindeman (1942) formalized the concept of trophic levels and linked them to Elton pyramids. Since Elton, ecologists have recurrently built pyramids and, along with Lindeman, have also reiterated paradigmatic magic numbers for the efficiency in matter transfer among the layers (generally 10%) which fit with many above-the-surface terrestrial ecosystems (Frontier et al, 2008). The simplified scheme of a pyramid holds true when the organisms may be unequivocally distributed in trophic levels, e.g., primary producers, primary consumers that feed on them, secondary consumers that feed on the latter etc. which is an emerging pattern of several terrestrial ecosystems.

Figure 10a shows the global distribution of biomasses for aggregated trophic layers of terrestrial organism based on data recently assembled by Bar-On et al (2018). To reduce the overwhelming weight on biomass of structural parts of trees only roots and leaves have been included in the computation of the values reported in the figure. The same computation made for the marine organism (Fig. 10b) shows a striking different pattern, with no pyramidal shape. Also for marine organisms the position in a specific level is to some extent arbitrary. For example a large part of photosynthetic pico-eukaryotes are mixotrophs but because of their crucial contribution in the production of organic matter for all the other organisms, they have been included in the level of primary producers. Likewise, the layer of bacteria and archaea above the primary producers for both systems is to stress the fact that they are consumers even if, they do not properly feed on primary producers but on part of their photosynthates.



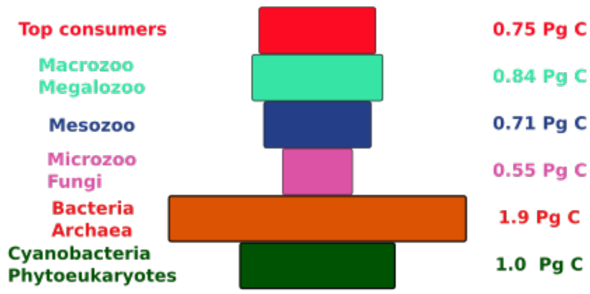


Figure 10. Distribution of biomass among different trophic levels. The selection of the level is based on the known prevalent position in the food web of the different groups. Mixotrophy has been ignored for marine photosynthetic protists.
a) terrestrial organisms; b) marine organisms.

The evidence that in many ecosystems the distribution of organisms does not follow the 'classical' eltonian shape but can have even an opposite shape, meaning that of an inverted pyramid, led to the introduction of the more general concept of bottom-heavy or top-heavy pyramids (e.g., Trebilco etal, 2013). Terrestrial food web display a prevailing bottom-heavy shape, with top consumers displaying much lower abundance and biomass than primary producers (Hatton et al, 2015). As mentioned above, this pattern would hold true even if the crucial contribution of the structural biomass of terrestrial primary producers would not be accounted for. By contrast, aquatic ecosystems display a full suite of trophic organizations with a prevalence of top-heavy layering of throphic levels (Woodson et al, 2018).

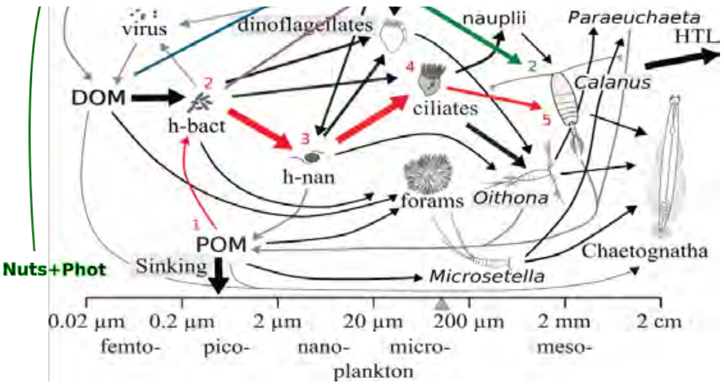


Figure 11. A sketch of a plankton food web including mixotrophy (blue and purple arrows) (modified from Basedowet et al, 2016)

A vital debate is going on about the mechanisms driving these patterns, with many analyses relying on scaling laws (Trebilco et al, 2013; Hatton et al, 2015; McCauley et al, 2018; Woodson et al, 2020). Despite the evidence that top-down pyramids prevail in marine food webs, especially in the pelagic domain, the implicit assumption behind the large majority of models of the pelagic food webs is of systems driven from the bottom, meaning that there is a lot of detail in formulating the modulation of primary producers activity by their essential resources, e.g., nutrients, light, trace elements, while less attention is invested in detailing the mechanisms by which consumers, and their dynamics shape the functioning of the web (e.g., Le Quéré et al, 2005). As a consequence, in many biogeochemical models, consumers are more a closure term than an active, crucial component in determining the fate of matter and energy flows in the communities (Eilertsen & Wyatt 2000; Stec et al, 2017).

Furthermore, the bottom-up approach tends to represent primary producers as passive transducers of energy and matter as long as they are available, overlooking the role that species-specific biological traits and life strategies may play in those flows (Stec et al. 2017).

Even a relatively simplified depiction of a plankton food web (Fig. 11) displays a lot of entanglement with many trophic links generating strong feedback loops.

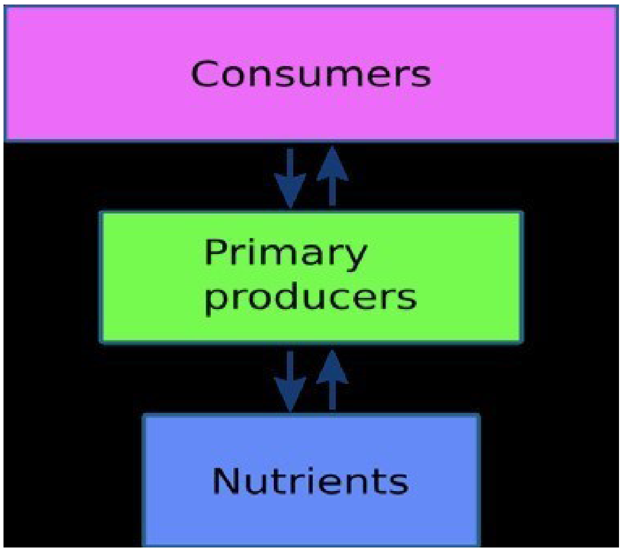


Figure 12. A highly simplified marine pelagic pyramid

The presence of those entanglement and loops allows also for a significant plasticity in the organization and fluxes of matter within the web, with numerous switches among different paths that allow for the matter produced by primary producers to be kept under control by all the other components (D'Alelio et al, 2016; D'Alelio et al, 2019). The size structure of plankton communities and its allometric constraints lead to the typical top-heavy pelagic pyramid which is the prevailing shape for most of time and space in the present ocean (Fig. 12) (Woodson et al, 2018). The processes behind those fluxes and links may be formulated with the classical equations by Riley (1946) (see below, with N, P and h, representing nutrients, primary producers and consumers, respectively) which describe the time change of nutrients, primary produces and all consumers, which better characterize the bottom-up view, i.e., nutrients and light →phyto → zoo, of the marine food webs. Many possible solutions of those equations, which means that many possible size of the boxes reported in Fig. 12, may result from their solutions, in dependence of the values of the rate coefficients associated to the three key components that are parametrized in the equations.

$$\frac{dN}{dt} = cPegh - P_r + mN_0 - N$$
$$\frac{dP}{dt} = PP_r - gh - \frac{v}{L} - m$$
$$\frac{dh}{dt} = hgP - r_h - fC$$

However, those rate coefficients are assumed constant, with no plasticity at the level of the organisms or of the whole community (see above), which has as a consequence that everything is basically shaped by the nutrient flux. This does not prevent the possibility of having top-heavy pyramids, since the combination of the turnover rates, the efficiency transfer and the size ratios among the components, all traits embedded in the parameters, tend to generate top-heavy pyramids (Trebilco et al, 2013).

All the above leads to Descriptor 5 of the MSFD whose first part reads 'Human-induced eutrophication is minimised.... Along with what has been discussed above eutrophication, which should be assessed either by '..oxygen deficiency in bottom waters..' or, more frequently, by chlorophyll a concentration, a proxy for phytoplankton biomass, would represent a bottom-heavy pyramid. However, even if they are generally transient in the pelagic environment, for example during spring blooms, bottom-heavy pyramids are not per se and indicator of a disfunction of the system. Also the chlorophyll a concentration is not per se a good metric for assessing the degree of eutrophication. Cloern and Jassby (2008) clearly showed that chlorophyll a concentration in natural systems may vary over four orders of magnitude. Therefore, even if it is the time derivative of chlorophyll a concentration that is taken as an indicator of eutrophication more than its absolute value, the criterion is still quite empirical and phenomenological because overlooks the question of why and on which time scales the system would invert the pyramid. As a matter of fact some upwelling systems reach levels of biomass in the same order of magnitude of systems classed as highly eutrophied (Walsh, 1988). However, they are generally considered 'healthy' and important providers of ecosystem services. This leads to the final point. During history, humans have intentionally eutrophied the land with agriculture, to keep the systems at an early stage of succession and with very low diversity (Margalef, 1968). This has favored the neolitic explosion and the birth of modern world. With marine environment we have had, at least for what eutrophication concerns, a more precautionary aptitude, which has reasons.

But this approach is motivated by the different food web structure of pelagic communities, as sketched before, but is also due to our still poor knowledge on how to properly manipulate them. This does not overcome the fact that we feed on much higher trophic levels of marine food webs than on land, but asks for a more in depth understanding of their dynamics, which would allow for a better management and to the possibility of converting a presently negative impact on a positive ones, for both Man and marine ecosystems.

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Session V
How to manage MSFD and enhance science-policy interface

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The MSFD as relatively "young" but complex socio-ecological legislation has by now generated a broad scientific community response and interests. Many research projects were and are conducted within Europe and beyond its borders, aiming to enhance science background of the MSFD assessments. But questions on how to manage the MSFD including better and enhanced science-policy interfaces or what practical mechanisms exist allowing suitable introduction of technical and scientific innovations are still not answered sufficiently.

The last session focused on some examples on how to tackle potential problems connected to the implementation of MSFD approaches for reaching an actual GES in the Mediterranean basin wide regional and sub-regional scales. The different experiences and point of views are given (scientific and policy makers) on the approaches including the South and North of the Mediterranean Sea. These examples will also showcase progresses in the ecological and environmental sciences that we have focused on in the previous sessions (about models, new concepts, approaches, tools and methods...) and on how these improvements can be introduce into MSFD as well as in the Regional Sea Conventions in order to maintain, observe, assess and understand good environment-ecological status of the marine ecosystems.

Main outcomes of the session and its discussion are:

- Science-based insight is a key element for the shared, consistent and coherent understanding of what constitutes GES across all EU marine regions. This is also remaining as a key challenge for a clear path for the common implementation of the MSFD; The lack of such shared vision leads to the inability to meet MSFD goals of GES for European Seas. Extended beyond EU marine borders, at the regional marine scales, such common understanding is also needed;

- GES assessments at the regional marine scales should be further organized, developed and implemented through the harmonized EU and Regional Sea Conventions frameworks; this will include common approaches and assessment methods, joint integrated monitoring programs and open, unified, user-friendly database management and supply. In addition, this will require innovative science research contribution into observation and evaluation methods, including development of GES indicators, and will need improvement in management and policy coherence between different EU and RSC frameworks.

- As an example, an improved regional coordination (EU and Barcelona Convention) over Mediterranean Sea, shall provide a platform that can connect and coordinate outcome-based goals and targets with a fully-fledged monitoring framework, using the best available science, that can also offer a basis for national indicator frameworks and capacity building formats at the local national scales;

- Unifying environmental, ecological, social and economic insights, that is providing ecosystem based approach to inform regional and local-national marine management decisions, including spatial planning, assessing the trade-offs and synergies among different marine uses and approaches will be a major scientific challenge in supporting blue growth and sustainable uses of marine resources, maintenance of all ecosystem services, and of good environmental status in the European Seas over the coming decades.

- Highlighting ecosystem-based approach as a key transition to sustainable pathways of marine ecosystems management and the conservation their services; this will also represent a challenge for science and management under the wholistic DAPSI(W)R(M frame.

Marine Strategy beyond borders, Part I

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In 2008, the Contracting Parties to the Barcelona Convention and its Protocols decided to progressively apply the ecosystem approach to the management of human activities that may affect the Mediterranean marine and coastal environment for the promotion of sustainable development (COP 15, Decision IG.17/6). This refers not only to an overarching principle cutting across all Mediterranean Action Plan (MAP) operations, but also to a specific process with an adopted implementation roadmap, including the definition of an ecological vision for the Mediterranean, the setting of common strategic goals and of a set of corresponding ecological objectives and indicators. The vision is for "a healthy Mediterranean with marine and coastal ecosystems that are productive and biologically diverse contributing to sustainable development for the benefit of present and future generations".

In line with this vision, the overall objective of the implementation of the Ecosystem Approach roadmap is to achieve and/or maintain Good Environmental Status (GES) of the Mediterranean Sea and coasts.

Contracting Parties adopted a list of 11 Ecological Objectives (EOs), addressing all key elements of the Mediterranean marine and coastal environment (COP 17, Decision IG. 20/4), further broken down into Operational Objectives, as well as GES definitions and associated targets (COP 18, Decision IG.21/3).

In view of establishing a coherent region-wide framework, the Contracting Parties adopted in 2016 the Integrated Monitoring and Assessment Programme of the Mediterranean Sea and Coast and Related Assessment Criteria (IMAP, COP 19, Decision IG.22/7). The IMAP is articulated along 23 regionally-agreed Common Indicators and 4 Candidate Common Indicators, covering for the moment 9 out of 11 EOs.

In this context, UNEP/MAP delivered in 2017 the first ever Quality Status Report for the Mediterranean (2017 MED QSR), endorsed by COP 20 Decision IG.23/6. IMAP implementation has since progressed with the establishment of national IMAPs, development of a centralized data collection and management infrastructure (IMAP Info System), refinement of technical specifications on IMAP common indicators, building of knowledge on candidate indicators, and development of methodologies for integrated assessment.

A specific Roadmap (endorsed at COP 21 with Decision IG.24/4) is currently under implementation for the preparation of a fully-data based Quality Status Report in 2023 (2023 MED QSR). This Roadmap is articulated along the following processes:

- Timely negotiation and agreement of Contracting Parties through the Ecosystem Approach Governance Structure at regional (and as appropriate at sub-regional) level on the scale(s) of monitoring, assessment and reporting;

- Development and agreement on necessary methodological tools and assessment criteria to allow and promote integrated assessment of GES at the level of EOs and to the extent possible, across relevant EOs;

- Full implementation of IMAP-based national monitoring programmes throughout the Mediterranean to enable the region to generate quality assured and real time data during 2020-2022;

- Delivery and operationalization of a user-friendly and SEIS-based IMAP Info System to collect and process data produced by IMAP-based national monitoring programmes;

- Development and implementation of Monitoring Protocols and Data Quality Assurance and Quality Control for IMAP Common Indicators;

- Continuous support and technical assistance to the Contracting Parties in relation to all the above areas

- Outreach to regional partners to provide inputs to the 2023 MED QSR, establishment of solid partnerships and development of a communication and visibility strategy for the 2023 MED QSR

- Regular and effective regional cooperation and

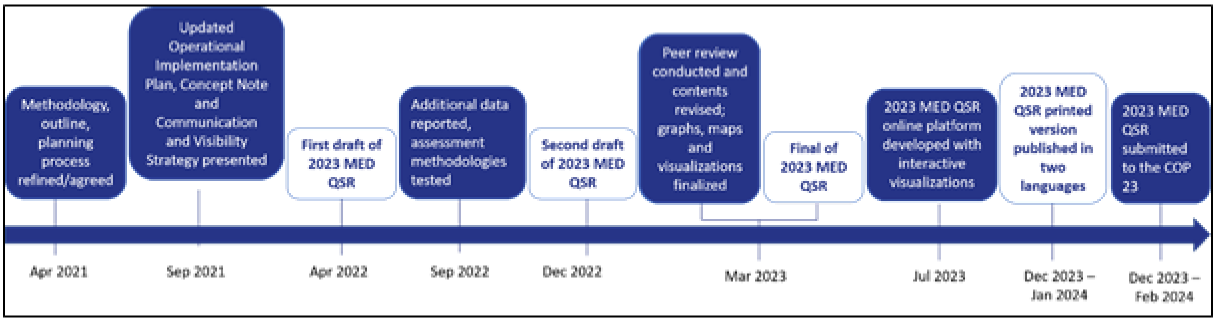

Figure 13: Timeline of delivery of the 2023 MED QSR (Credit: UNEP/MAP).

coordination with the Contracting Parties, through Correspondence Monitoring Groups (CORMONs), under the guidance of the Ecosystem Approach Coordination Group.

The scope of the assessment for the 2023 MED QSR will be regional/subregional, based as appropriate on data and information provided by Contracting Parties, and deriving to the extent possible from the national IMAP-based monitoring programmes around the region. Based on the progress expected to be achieved on the integrated assessment methodologies, efforts will be made for integrated assessment within and, to the extent possible, across the IMAP clusters (i.e., Pollution and Marine Litter; Biodiversity and Non-Indigenous Species; and Coast and Hydrography), and to address interrelations of pressures and impacts using an optimal Driver-Pressure-State-Impact-Response Framework (DPSIR) approach.

Taking into account the experiences from MED QSR process the most important recommendations for the Joint Action on S4GES on how value can be added to assessing a good environmental status are:

- Focus future data collection activities, such as the planned joint oceanographic cruise, on ecosystem elements and functions that are currently less monitored (e.g., food webs and seafloor integrity), especially in the Mediterranean. This may also support testing and validating integrated assessment methodologies.

- Strengthen collaboration with Regional Sea Conventions on capacity building, development and testing of integrated GES assessment methodologies, and sharing of best practices on joint monitoring and integrated GES assessment.

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Marine Strategy beyond borders, part II

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The growing awareness of the intense pressures causing environmental degradation of the Mediterranean's natural wealth signals the need for a sustainable approach. Scientific knowledge, Maritime strategies and citizen science applied to our shared Mediterranean Sea are the basis for understanding and protecting it. Science, Society and policy need to be accurately linked in Tunisia in order to effectively protect the marine resources and efficiently maintain the Good Environmental Status in the Southern basin.

In the light of the MSFD descriptors, Tunisia have developed marine strategies and scientific observational systems and studies in order to evaluate the GES of the Mediterranean Sea through criteria and methodological standards. One should consider as examples, the Ferrybox system including the sampled Sea parameters in real time, CTD sensors, auto-sampler, filtration system to collect microplastic samples, dynamic web-application related to Ferrybox data to insure a long-term follow-up. A special consideration is dedicated to enhancing the science-policy interface, for that aim, a National Hub will ensure building a shared information system, based on trustworthy, science-based data, from all parts of the Tunisian society, outreach activities about citizen science, implementation of BlueMed priorities in Tunisia based on National and International projects, etc.

The competence of the marine scientific community should thus be made available to the policy implementation process, and a long-term networking should be taken into account in order to bridge the gap between scientists, decision makers and stakeholders, with a special interest to citizens who are the main actors of change.

One should bear in mind that the GES is a complex affair that highlights the need for a multidisciplinary scientific research while taking into consideration the socio-economic and political forcing. As most important recommendations, we believe it is crucial to further investigate the complexity of MSFD by combining strategies in the light of all descriptors.

In this regard, the first descriptor "Biodiversity" is of a paramount importance and a special focus should be dedicated to it, as well as marine vulnerable habitats restoration including areas under anthropic pressures. In doing so, monitoring the effect of long-term cumulative stressors (while taking into consideration noise and industrial parameters) affecting the human and ecosystems health, via an advanced web-mapping tool which allows real time assessment should be stressed.

Accordingly, a high priority should be dedicated to implementing pilot actions into areas where an ecological information is already available and enabling monitoring protocols to track changes in species abundances, trophic relationships and overall biodiversity (Aguzzi et al 2019).

The 7th descriptor "Hydrographical conditions" should be also valued in order to assess the contribution of shipping waste to marine litter in addition to biological, chemical and physical parameters. In this regard, INSTM has acquired a FERRYBOX system installed since February 2016 on board the C/f Carthage ferry of the Tunisian Company of Navigation (CTN).

As a first step, Tunisia has identified two main shipping routes within the Mediterranean, which were selected for the study of biological, chemical and physical parameters in addition to Marine Litter distribution patterns along its course.

The most important advantage in this technology is its high frequency measuring ability. The parameters concerned by this system are temperature, salinity, turbidity, oxygen and Chl-a.

Furthermore, H2020-CLAIM team members from the INSTM Tunisia have recently added two new technologies to the Ferrybox installation (an Auto-sampler and a filtration system for micro-plastics). These technologies will maximize the number of samples, determine the nature of the polymers and explain their dispersion by coupling them with hydro-biological data, while being combined to a Ferrybox web application allowing a real time monitoring of the evolution in surface waters (Public access to the FerryBox web application: 41.229.139.78:8000).

It is thus worth mentioning that the main shortcoming of this equipment is the study of parameters distribution in surface waters, for this reason, INSTM will be developing a further analysis related to three major fields:

- Study the distribution of litter density and litter hotspots through advanced modelling and implementing a hydrodynamic model in this area while taking into account the long-term correlation between biological, chemical and physical parameters, in addition to establishing further investigations depending on bathymetry,

- Coupling surface parameters to biological processes while considering weather forcing to study the influence of climate change occurring on a larger scale and time range; and

- Combining Ferrybox in situ data to satellite imagery and altimetry, which will be of a paramount importance in identifying water masses properties and the long-term follow-up of a higher range of parameters.

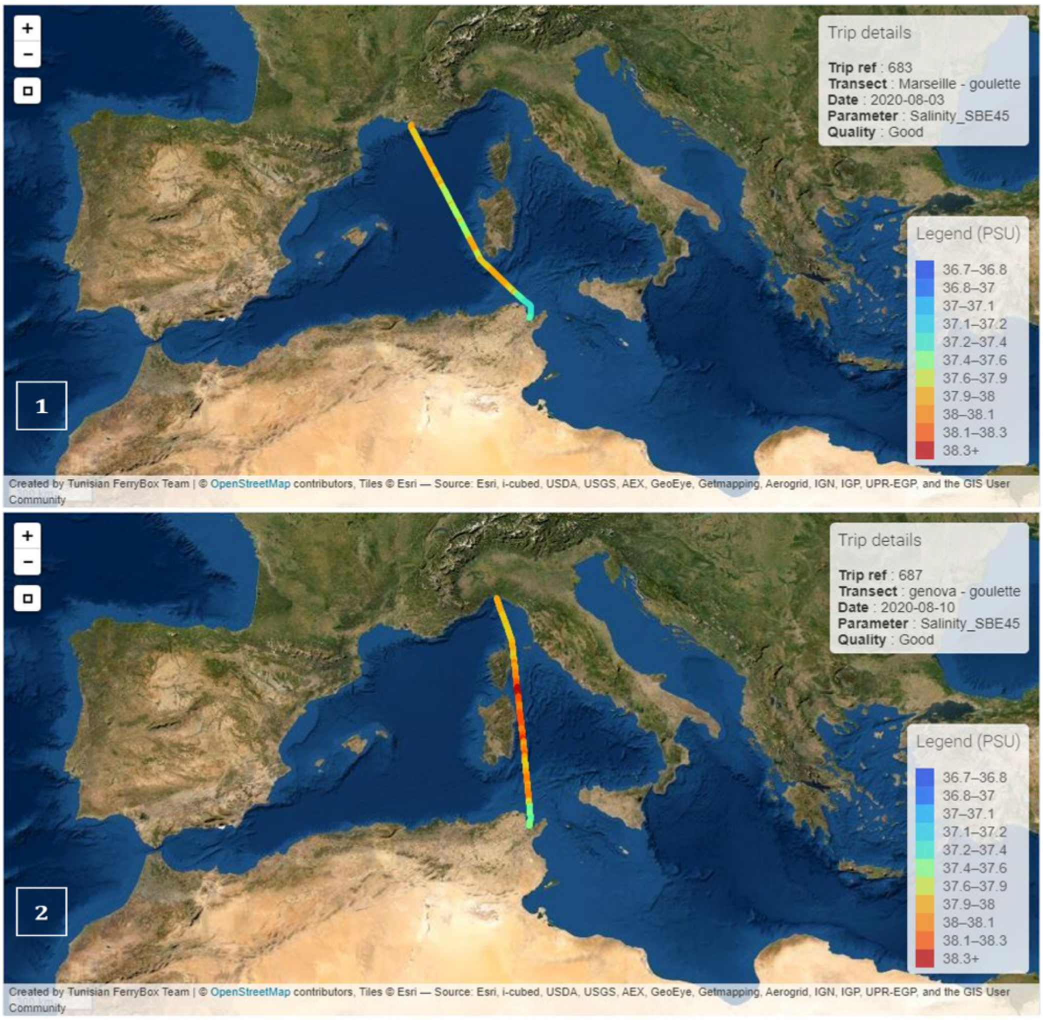

Figure 14: Ferrybox web-application outputs[2] – a figure showing two maps while analyzing the same parameter "Salinity" (1) highlights a transect from Marseille to Goulette (2) highlights a transect from Genova to Marseille (metadata are shown in the top right box related to trip details). The database and its normalizations are submitted to SeaDataNet standards. The main charts accessible via the Ferrybox web application are: Transect plots, transect maps, time series and scatter visualizations. Regular Users can take advantage from the actual results to visualize, understand and request FerryBox data.

As an example, the map (Fig.14) shows two trips details, a color bar specific to each parameter type, and a popup on mouse click displaying the point's position and parameter value. In order to visualize the transects plot, the user has to select:

- Transect: select a trip reference and path

- Parameter: select a parameter in the list: Salinity, temperature, Oxygen, Chlorophyll and turbidity.

- QC: in this example qc= 1

It is also important to highlight that efforts should be made to develop the distribution patterns of specific litter categories most relevant to shipping. Subsequently, correlations between shipping routes and litter distribution, with particular emphasis in litter density distribution. Moreover, data pertaining to litter types in the areas of interest will be analysed in order to obtain indications regarding the potential origin of the waste as well as to examine correlations with the waste typically generated by shipping.

Lastly, Mediterranean synergies between research institutes related to this web application and advanced observational analysis should be explored in order to enlarge the parameters range and include further investigated areas.

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Public access to the FerryBox web application: 41.229.139.78:8000.

How could non-EU countries contribute to a better understanding of Mediterranean dynamics and cross-border connections? Examples from Morocco

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Over the last decades, human-induced pressures, exacerbated by climate change, have increasingly affected the Mediterranean region. The riparian countries are increasingly aware of these growing risks and recognize the need for regular and adaptive monitoring to anticipate these adverse phenomena. They also recognize that good policy decisions rely on sound knowledge, targeted research and innovation, and dissemination of this knowledge to all stakeholders. Both BlueMed in its Implementation Plan and the Ocean decade Workshop "The Mediterranean Sea We Need for the Future We Want", have stated that to address these trends, further developments in effective monitoring and robust predictions of the coastal areas are crucial to support efforts for sustainable development and resilience of societies and ecosystems. The challenge is that the Mediterranean is a shared space and its northern and southern shores cannot be treated separately. This is why cooperation and partnership are keys to successful implementation of the Mediterranean GES. So, how could non-EU countries, like Morocco contribute to a better understanding of Mediterranean dynamics and cross-border connections?

Observation and monitoring activities

Among the environmental observing and monitoring programs carried out in Morocco, which can contribute to the good environmental status of the Mediterranean, we can mention:

- In terms of monitoring of marine ecosystems, the National Institute for fisheries (INRH) conducts seasonal oceanographic cruises in the Mediterranean and Atlantic Ocean. The monitored variables are: temperature, salinity, turbidity, dissolved oxygen, nutrients, fluorescence, chlorophyll a, phytoplankton, zooplankton, etc. INRH also regularly monitors the health of shellfish production areas. The recently acquired glider in the Al Hoceima bay in the framework of ODYSSEA Project, will be used for documenting and mapping sea mammal populations, sonar ping echo, maritime traffic, health and conditions of marine habitats, and human noise. Marine ecosystems are also monitored by remote sensing.

• In terms of pollution monitoring of the Moroccan Mediterranean coast, the quality of bathing water and of beach sand are monitored seasonally in 73 beaches and 20 beaches respectively. The monitoring sites are selected based on the importance of attendance, shoreline morphology and potential pollution risks (wastewater discharge, river mouths, ports, etc.).

Regarding the marine litter and especially plastics, there is not yet a formalized institutional framework to regularly assess marine litter and its impacts in Morocco, but there have been many initiatives in recent years to develop a national strategy to fight against this scourge. The flagship initiatives are:

• The "Plastic-free Littoral or LISP" Project: The Department of Environment has concluded a Technical Assistance (TA) project with the World Bank for the development of the national strategy LISP dedicated to the reduction of marine pollution by plastic waste and to the promotion of circular economy models in coastal regions. This TA is part of the WB ProBlue program. The first step of this strategy, already finalized, consisted of a diagnostic analysis, the operational objectives of which were: (i) analysis of national policies in relation to the management of waste in general and plastic waste in particular; (ii) assessment of driving forces, pressures, state and both ecological and socio-economic impacts of marine plastic litter; (iii) evaluation of the country's responses to this problem through all the initiatives; (iv) the identification of Hot-Spots and sensitive areas for prioritization of coastal territories where actions should be implemented in the very short term.

• In 2016, Morocco has passed a law that prohibits the manufacture, import, export, marketing and use of plastic bags.

• The National Program for Collection and Disposal of Used Plastic Bags and promotion of paper and fabric bags.

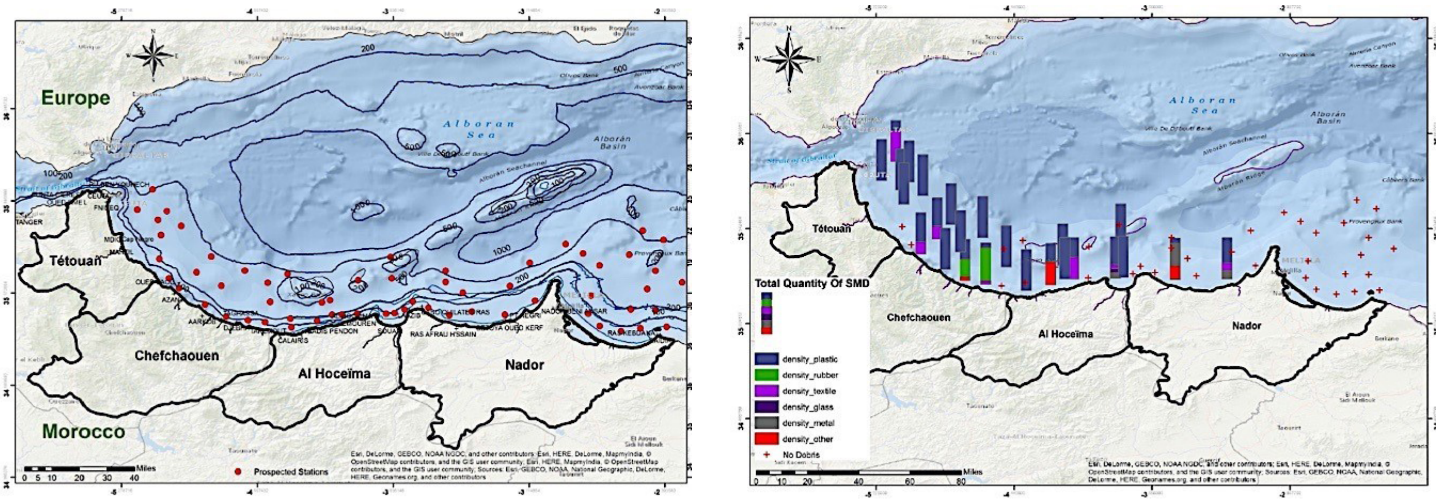

Figure 15: Left - location of the study area between Cap Spartel (5°50W) and Saidia (2°17W), and the sampling network. Right - distribution and density of each category of marine debris (kg/km^2) (Source: Loulad et al., 2019).

- In 2014, imposition of an eco-tax on the sale, ex-works and import of plastics. The purpose of this tax is to finance the emergence and development of the plastic recycling sector and the integration of the existing informal sector.

- At the regional level, Morocco participated to SwitchMed Pilot projects for the implementation of the regional plan on the management of marine litter through "Adopt a beach" and "Fishing for Litter" projects.

- In addition, capacity building and participatory workshops were organized as part of the SWIM/H2020 Project, the WestMed and BlueMed Initiatives.

The preliminary scientific evaluations, based on the analysis of Seafloor Marine Debris (SMD) in the Moroccan Mediterranean using data collected during trawl surveys from 2012 to 2015 showed that (Nachite et al. 2018; Loulad et al., 2019):

- Plastic materials reached 73% of the total debris catch;

- The majority of them were found closer to the coast and in two specific depth strata (i.e. 50–100m and 200–500 m).

- The abundance and distribution of SMD were strongly influenced by the local anthropogenic activities and by rivers inputs.

Other initiatives in favor of the GES are:

- The National Coastal Plan (Approved in 2020)

- The Atlas of the littoral (DPDPM, 2018)

- The Regional Coastal Development and Protection Scheme (SRL): Regulatory document stipulated by the Coastal Law.

Data access and sharing

The Department of Environment has set up the National Environmental Observatory (ONEM) whose missions are (i) to assess the state of the environment, (ii) to define and ensure the updating of sustainable development indicators (SDI); and (iii) to disseminate and share environmental data.

The Regional Information Systems for the Environment and Sustainable Development (SIREDD), which were established, in each Region, in application of the Law relating to the right of access to information, have as main objective to provide information on regional data, via a dedicated website and facilitate access to information for the benefit of the various actors. In the two regions of the Moroccan Mediterranean, a SIREDD is currently being operationalized. This system includes the "waste" component and display all the SEIS, SNDD, SDG indicators related to the waste sector.

In the framework of the Shared Environmental Information System (SEIS), Morocco elaborated recently (2020) the national report on the implementation progress of SEIS II South, which analysed all the ongoing initiatives in terms of solid household waste, industrial discharges and domestic wastewater, and identified the measures to be taken to meet the SEIS objectives.

Dissemination & outreach

The main activities carried out include:

- Organization of several "clean-up" operations and awareness-raising campaigns for decision makers and the public;

- Remote consultation on Blue Economy with all the concerned stakeholders (Economic sectors, environment, institutions, private, academia, NGOs), in the framework of the WB Blue Economy project;

- Online consultations for the "Littoral without Plastics" Project funded by the WB;

- Strengthening of participatory coastal management for the reduction of marine litter in the Tanger-Tetouan-Al Hoceima Region, carried out under the SWIM-H2020 project, with TA from the European Union (EU).

- Organization in 2020 of a national WestMed event on Blue Economy: What challenges, opportunities and priorities for Morocco?

Weaknesses & needs

The implementation and sustainability of the follow-up activities show some weaknesses and needs in:

- Science-policy interface and mechanisms for dialogue to allow research projects and policy actors to interact more and regularly. Indeed, when collaboration between science and policy exists, it is often project-dependent and thus short-lived with limited capitalization over time;

- Sharing data and outputs produced by research and innovation projects through common platforms and observatories: We need to establish mechanisms to exchange experience and disseminate knowledge, information and best practices and train on the new products;

- We need to better structure and consolidate the South-North partnerships;

- We need to do more than make data available: build tools and services ready to use for stakeholders;

- We need to pursue science-policy integration as a cross-cutting priority and build structural mechanisms to manage complexity;

- We need to enhance financial resources mobilisation for regional support programmes.

Most important recommendations for the assessment of GES are:

- Strengthen research on assessing the cumulative effects of short-term climate variation and anthropogenic pressures and improve the analysis of risks, so that the time frames between scientists and decision-makers are in phase;

- Facilitate the access to reliable and comparable scientific data across the Mediterranean countries through shared platforms;

- Capacity building formats: we need regional organizations to provide practices and solutions, not just guidelines and concepts. Education to complexity and building capacity in sustainability science, with their new sets of indicators are also needed.

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Biomonitors and biomarkers in marine pollution monitoring: Possibilities and Limits

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The Mediterranean Sea is exposed to various and complex pollution from both industrial and urban effluents. The molecules generated by this pollution are susceptible to alter the physiology the reproduction of marine organisms. To optimise without constraints, the exploitation of marine resources, one of the major challenges is to distinguish between "clean" and polluted ecosystems.

Considering the disadvantages of using sea water and sediments in pollution monitoring, marine organisms such as bivalves were shown to be successful Bioindicators of pollution. In fact, these organisms accumulate contaminants usually from water and food. The accumulation reflects only the bio-available fraction and gives us information about the health status of on considered ecosystem. Different monitoring programs such as RNO and Mussel Watch are based on Mollusc bivalve model.

Biomonitoring programs based on measuring contaminants in marine organisms are interesting from a human health point of view. However, it does not give information about the toxicological significance of pollutants accumulated and does not indicate the health status of the organisms particularly because xenobiotics can be stored in various forms such as insoluble precipitates and concretions. Consequently, biomonitoring programs are now involving biomarkers. These are measurable parameters at different levels of biological organisation, molecular, cellular, or physiological. They traduce changes in the metabolic regulatory processes resulting from the effect of anthropogenic stressors. We can detect and quantify the biochemical interactions between a contaminant and its biological receptor in the living organism. In such case we can determine pollution concentrations needed to initiate this response which is assumed to be lower than those required to provoke a life-threatening situation for the organism or a degradation of the ecosystem. These early warning systems are called a biomarkers. In the last decades different research groups have focused on the validation of a battery of biomarkers and have been involved in biomonitoring program at the Mediterranean level. For that we need various and complementary approaches: in vitro, in vivo, in situ, in situ transplantations, and in vivo transplantation. They allow the validation of few Biomonitors and Biomarkers. Nevertheless, one of the crucial questions is about the variability of the response in relation with both biotic and abiotic factors. According to some researchers, the signal to noise ratio is a key issue allowing the validation or not of a considered biomarker.

More recently an innovative approach based on ex in vivo experiment was investigated, it has the advantage of limiting animal experimentation and could open new perspectives for pollution biomonitoring.

Most important recommendations for the Joint Action on S4GES on how – from your point of view and field of expertise – we can add value on assessing a good environmental status:

- Bio monitoring approach needs to rely on various methodologies (in vitro, in vivo, in situ, transplantations). In fact, they bring complementary understanding of the responses

- Biomarkers are early warning systems, the are useful if validated considering Biotic variations. Moreover, owing to the complexity of contamination, a multi-marker approach is needed.

- As suggested for the ocean decade, entrepreneurship is a key issue. Innovative ideas dealing about new solutions and systems for monitoring needs to be encouraged.

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How to manage the Marine Strategy Framework Directive machine: what are the keys

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The Marine Strategy Framework Directive (MSFD) represents a challenge for science and management, since it is a complex socio-ecological legislation, requiring monitoring and assessment of 11 qualitative descriptors and multiple ecosystem components, from plankton to mammals, using data coming from very different sources (Figure 16). The assessment must be undertaken under the ecosystem-based management approach (Borja et al., 2010). However, there is only one big idea in marine management: How to maintain and protect the ecological structure and functioning (which is in the MSFD), while at the same time allowing the system to produce sustainable ecosystem services from which we derive societal benefits (which is in the Maritime Spatial Planning Directive (MSPD) and the Blue Growth) (Elliott et al., 2018).

Figure 16: The complexity of monitoring data, multiple ecosystem components and habitats, necessary to assess the environmental status of marine waters, under the Marine Strategy Framework Directive.

The problem is how to reconcile both concepts, under a framework such as the DAPSI(W)R(M), in which the socio-economic Drivers promote human Activities, which produce Pressures and changes of State at sea, which result in Impacts on the environment and human Welfare (ecosystem services), needing Responses and management Measures, to reduce pressures and impacts (Elliott et al., 2017). Taking into account this framework, my personal keys for a better management of the MSFD machine can be summarized into four blocks: (i) organization and governance; (ii) monitoring (acting on the APSI(W) of the framework); (iii) assessment, on I(W); and (iv) management, on R(M)DAP.

The keys of each block include:

i) Organization and governance: take always knowledge-based decisions; use existing data as far as possible, in open access or national monitoring networks (Borja et al., 2019); practice flexibility during the whole process, avoiding continuous changes in methods; promote cooperation within and among states, at regional level (Soma et al., 2015; Cavallo et al., 2019); establish strong links between research and policy, using European and national projects, including all kind of stakeholders (Mea et al., 2016); avoid endogamy, using multiple experts, origins, multidisciplinarity and interdisciplinarity;

ii) Monitoring: design adequate networks to cover gap data (Patricio et al., 2016); use simple but effective methods, avoiding complicate and expensive methods (Mack et al., 2020);

iii) Assessment: use quantitative methods and thresholds (Borja et al., 2012, 2013; Rossberg et al., 2017); use expert judgment if necessary (Elliott et al., 2018); use harmonized, calibrated and validated methods (Uusitalo et al., 2016); use integrative methods, avoiding the principle 'One-out, all-out' (Borja et al. 2016); make all data obtained open access (Beck et al., 2020); and

iv) Management: design Programmes of Measures which can really contribute to achieve Good Environmental Status (GES) (Börger et al., 2016; Murillas-Maza et al., 2020); use adaptive management (Bigagli, 2015); and use real ecosystem-based management (Borja et al., 2016).

To conclude with a positive message, we can achieve GES, within the MSFD, and reconcile it with the objectives of the MSPD (and Blue Growth), if:

- Monitoring is adequately designed, coordinated within the same eco-region and using adequate resources;
- Any activity at sea is subjected to adequate evaluation of pressures and impacts produced, together with an investigation of its interaction with other activities;
- These activities are planned taking into account the assimilative capacity of the system;
- Harmonized methods are used in the whole implementation process;
- Ecosystem-based management approaches are operational and really applied;
- Methods for monitoring and assessment are simple (but not simplistic), based on science;
- Adequate quantitative targets and thresholds are set for indicators of GES;
- The programme of measures is designed to address the pressures preventing achieving GES;
- Integrative assessments (ecosystem-based approaches) are undertaken regularly, based upon the best knowledge available; and
- Socio-ecological marine ecosystems are considered in a holistic way, including humans as part of the ecosystem.

Hence, the most important recommendations for the Joint Action on S4GES on how – from my point of view and field of expertise – we can add value on achieving a GES, are summarized in those 10 items commented above. Reading together the first initial of each item, it can be seen the name 'MATHEMATICS', meaning that assessing the status under the MSFD and achieving GES must be based upon the best quantitative knowledge available, not (or not only) on qualitative data. This will make the assessments more comparable, harmonized and transparent.

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Final Remarks & outlook: Musing on the concept of Good Environmental Status: the complexity of the status and the status of complexity

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The recently approved JPI Oceans Joint Action 'Science for Good Environmental Status' (S4GES) promotes and coordinates integrated actions leading to consistent views on the assessment and achievement of the Good Environmental Status (GES), the final and essential goal of the Marine Strategy Framework Directive (MSFD). Fostering an integrative, holistic, ecosystem approach, the MSFD considers the marine environment as an ensemble of functional units with complex interactions, fully connected with the socio-economic drivers. This implies a better and deeper understanding and assessment of the stability, resilience and productive capacity of the marine environment (all relevant aspects related to the definition of the GES) characterized by complex, interacting biotic and abiotic processes, prevalently displaying a non-linear dynamic.

In brief, the Joint Action S4GES aims at raising a debate on the hiatus existing between the unquestionable, very general concept of GES and the difficulty of defining a metric for it, beyond a set of prevalently empirical criteria. It also aims at analysing and discussing whether the ecosystem view can be expanded so as to include the governance, which is an essential player for the implementation of the MSFD, and ultimately the sustainable use of the sea, but it is generally seen as being outside it.

The workshop: preliminary and emerging outcomes

The workshop 'Musing on the concept of Good Environmental Status: the complexity of the status and the status of complexity' held in December 3-5, 2020 was the first meeting organised in the context of S4GES and provided an inspiring multidisciplinary scene on which to build to refine the 'definition' of GES and to help in improving robust approaches to its assessment.

The exercise to share knowledge and shaping new ideas on how various scientific disciplines are dealing with similar problems either in general and in other scientific contexts (soil science, human microbiome science, forest science, agronomic science, mathematical science of dynamic and non-linear systems, etc.) and how it could support a more robust and appropriate assessment of GES, might be well-synthesized by the following three points:

- The GES definition and assessment represent a 'complex affair' for the scientific community and, deeply including socio-economic, governance and political forcing, calls for a really multi- and interdisciplinary science action (see presentations by Granum Carson and Moretti).

- It is urgent to 'expose' the MSFD community to an even wider spectrum of disciplines and scientific expertise to perceive and acknowledge the challenge of a comprehensive and convincing GES definition and assessment.

- Since the GES rightly remains the 'Holy Grail' of the MSFD, the 'MSFD-community' needs to be actually and effectively open to exploit robust mathematical tools, dedicated to a comprehensive analysis of the investigated systems, to be able to achieve it.

The need to develop, even for a temporary use, criteria and tools to support decisions was stressed by W. Bonne and Á. Borja. Many presentations at the workshop evidenced that several scientific communities face similar problems, e.g. the need to develop operational strategies and the difficulty to design them properly because of a partial understanding of how the systems function. D. Eveillard, F. Falcini, G. Masciandaro, M. Josè Sanz, and T. van Rossum illustrated their cases and the possible improvements at reach.

Deeper reflection needed

Another important point emerged from the presentations and during the discussions. i.e., that data, by themselves, are generally insufficient to predict the (eco)system trajectories in the future, if they are not framed in a mechanistic theory (e.g., A. Vulpiani), that allometric scaling models may allow to derive general simple rules on how certain systems function (e.g. A, Maritan), or that some empirical criteria derive from consolidated views applied to all systems, that do not always consider the specificities of the system considered (e.g., M. Ribera d'Alcalà and P. Mariani).

A specific effort has to be done to identify the essential equations and models to properly deal with multidimensional data in the context of MSFD for a proper assessment of GES because, often, the devil is in the details (see presentation by L. Dubroca). Semi-quantitative approaches, in robust model context, could offer a good way to capture the core of variability of the system with a good accuracy and robustness (although without a hyper-precision) [see presentations by C: Gaucherel and, again, P. Mariani].

Another crucial aspect raised by the discussion is related to the definition of a 'reference point' for the system functioning. Actually, anthropic impact significantly changed evolution trajectories of the Earth system and trying to set the value of a state variable looking for 'pristine' values is a sort of chimera. While prediction is among the most challenging objectives Science faces, there was a general consensus that a deep, conceptual effort to build solid knowledge bases about the functioning of the marine ecosystem and possible reference states, would also contribute to identify trajectories of the system evolution in the future.

The definitely positive development of the workshop has been possible also thanks to the insightful and stimulating role played by the chairs (S. Azaele, F. Falcini, P. Mariani, D. Iudicone, and J. Tronczynski) and by the active attitude of all participants, despite the virtual format that had to be forcefully adopted.

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